

Quasi-Elastic Scattering of Neutrinos and Antineutrinos at MINERvA

Joint Experimental-Theoretical Physics Seminar

10 May 2013, Fermilab

David Schmitz, University of Chicago

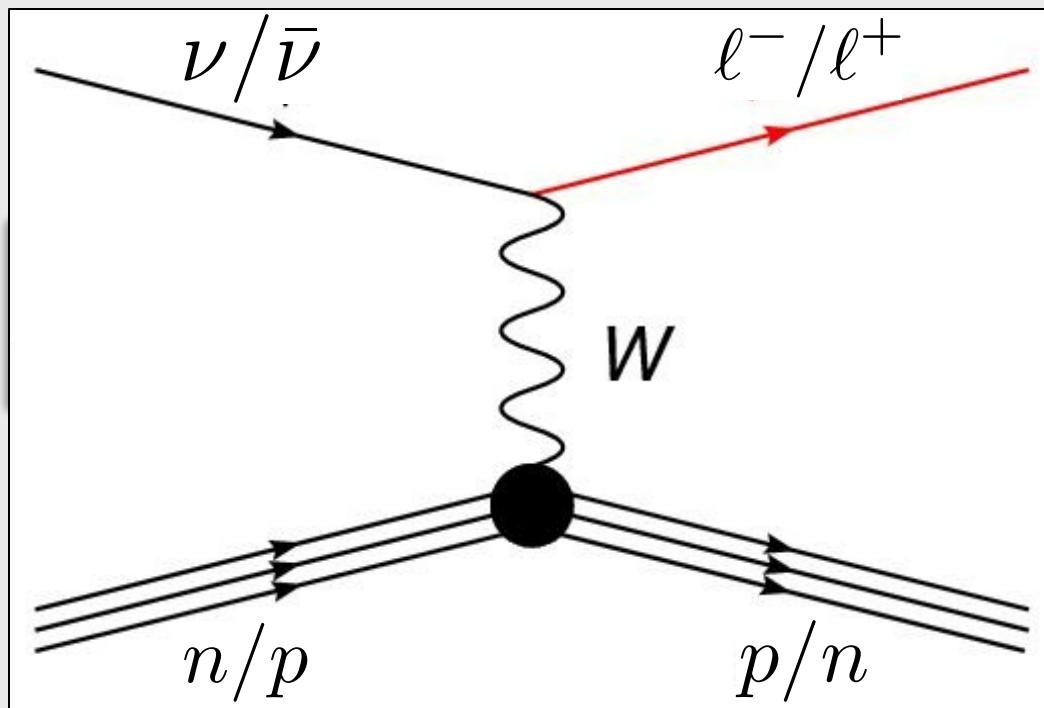
Some Opening Remarks

- The physics of neutrino-nucleus scattering is an important component of the on-going global effort to reveal the complete nature of neutrinos
- Scattering from heavy nuclear targets in neutrino experiments introduces a level of complication whose impact needs to be understood
- Modern experiments are providing large, detailed data sets to better understand these processes
- Close ties to nuclear physics. Both in terms of expertise and valuable complementary measurements (electron-nucleus scattering)
- These measurements are needed to improve ν -N modeling for use in future neutrino experiments

Outline

1. Charged-current quasi-elastic (CCQE) scattering
 - Historical treatment vs. recent considerations
2. MINERvA's measurement of QE scattering for ν and $\bar{\nu}$
 - The experiment
 - Isolating a QE sample
 - Systematic uncertainties
 - Interpretation of the results ($d\sigma/dQ^2$ and hadron energy)
3. Future outlook
4. Closing remarks

What Is Quasi-Elastic Scattering?



$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

CCQE scattering

Neutrino or antineutrino scattering from a free or bound nucleon

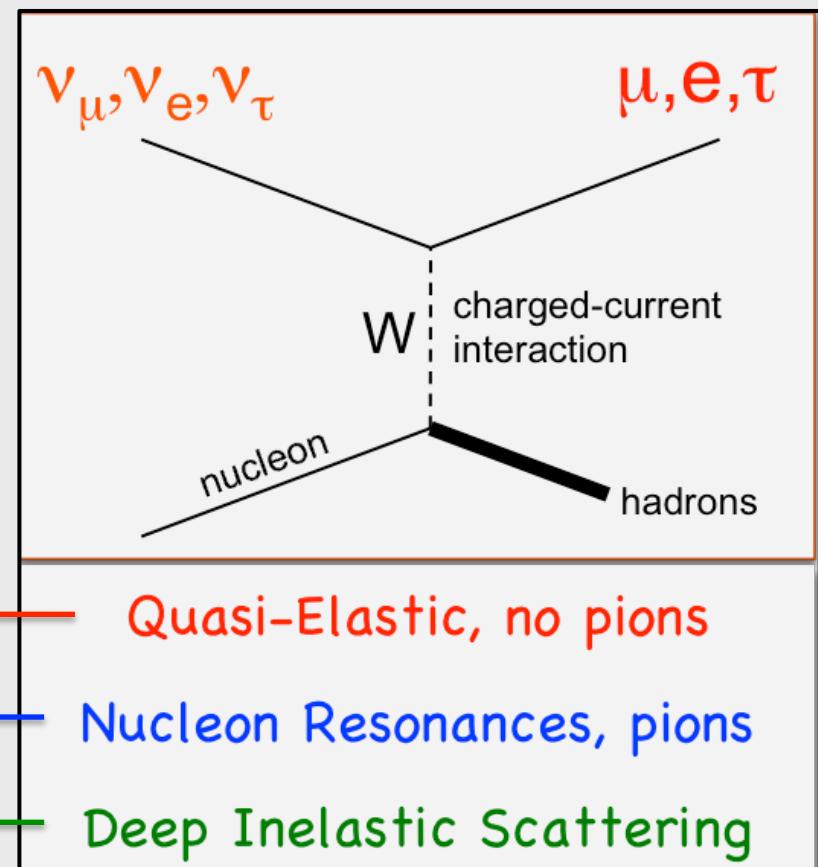
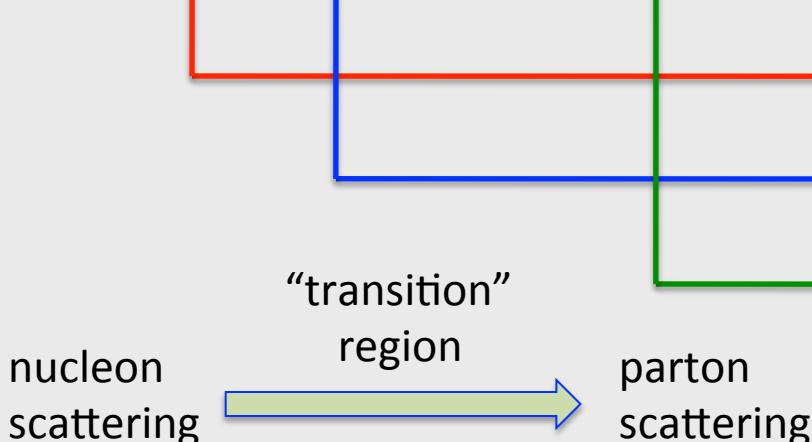
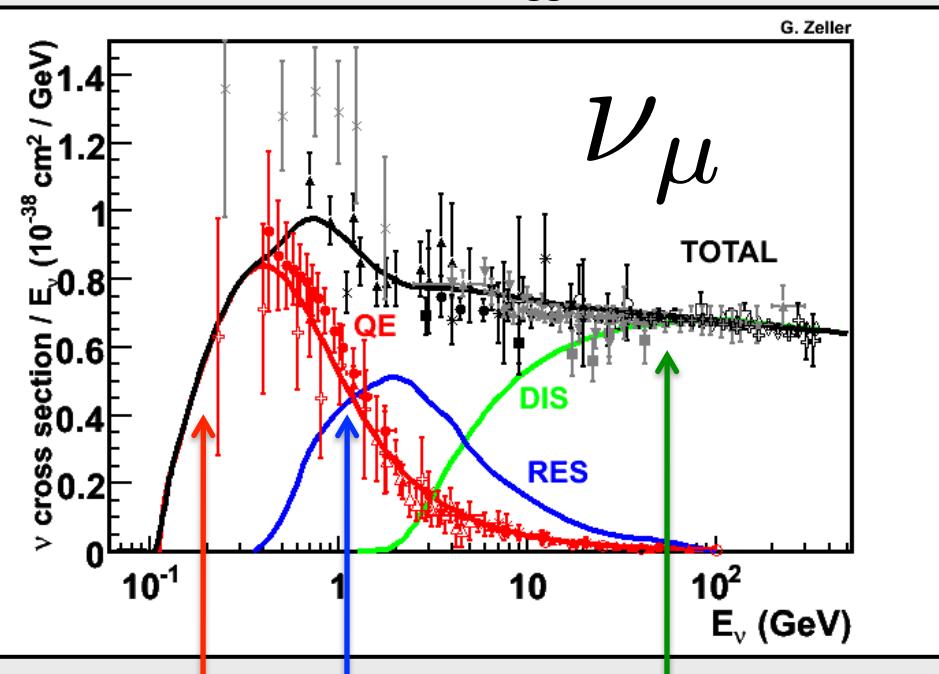
No pions in the final state

Neutrino transformed to a charged lepton

Identify flavor and determine neutrino energy (sort of a 'standard candle')

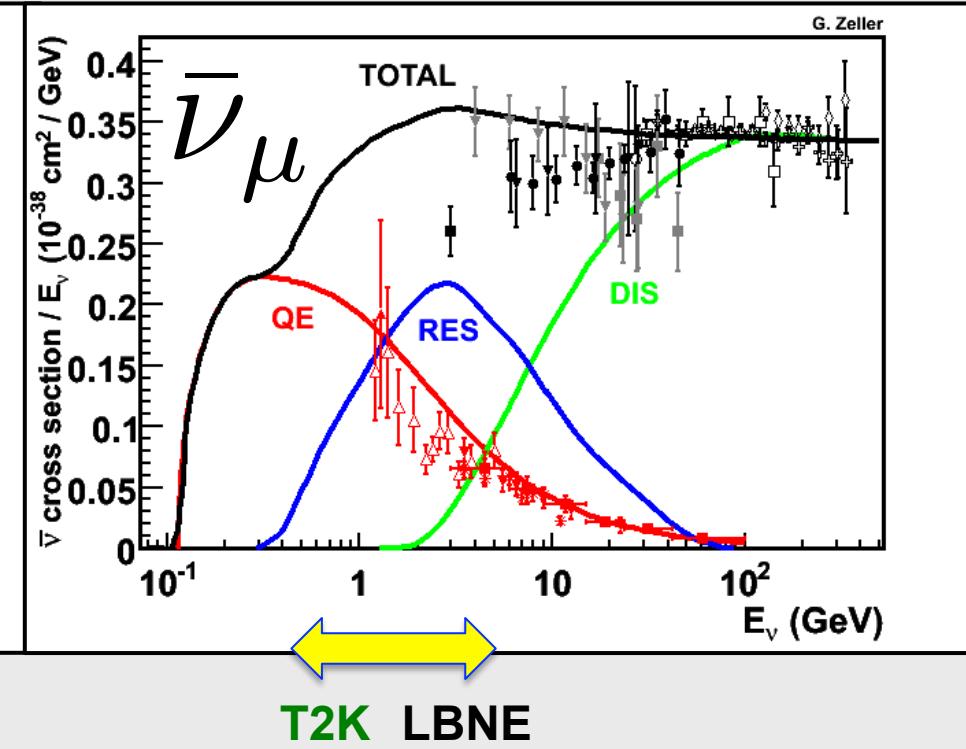
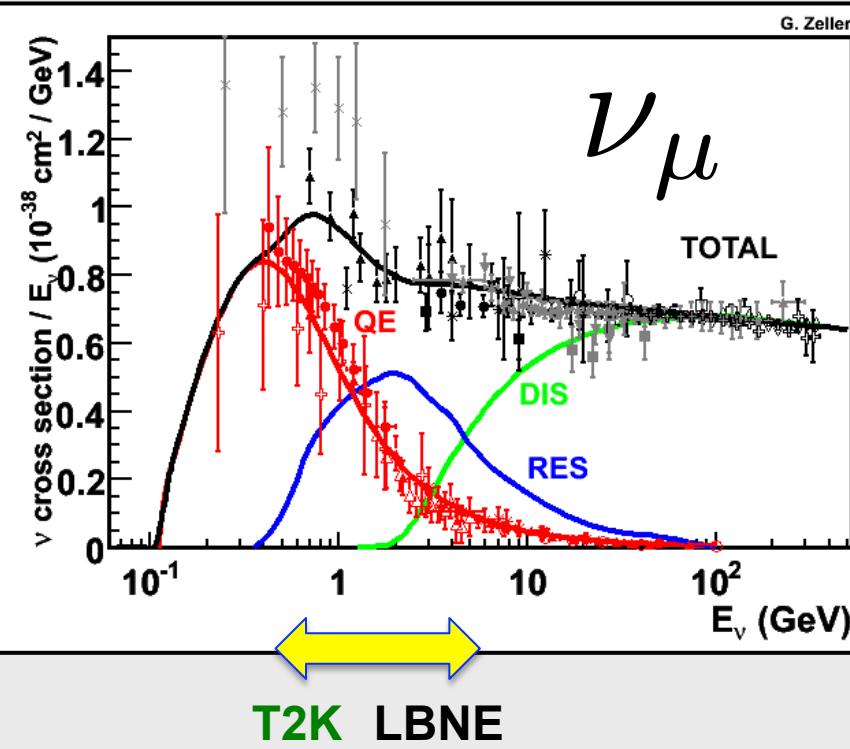
What Is Quasi-Elastic Scattering?

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012



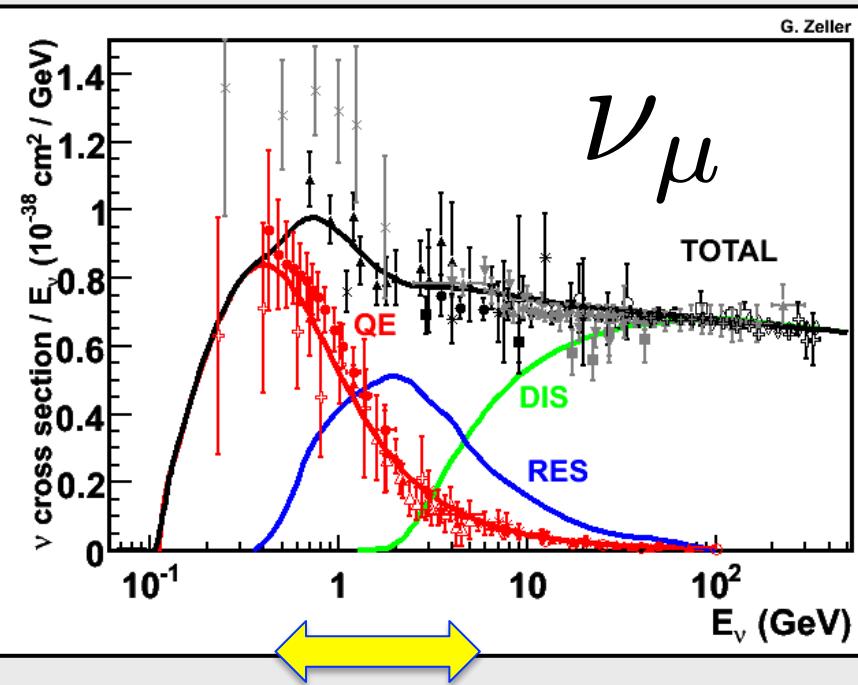
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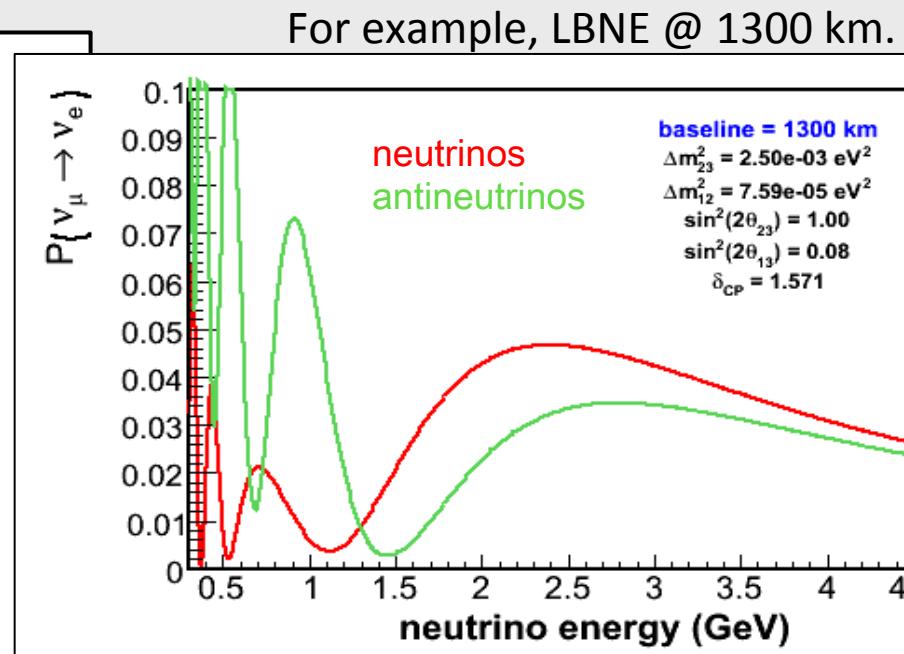


Accelerator neutrino experiments in the energy region most complicated by nuclear environment.

What Is Quasi-Elastic Scattering?



T2K LBNE
BooNEs NOvA



Compare oscillation probabilities as a function of neutrino energy for ν and anti- ν

Neutrino-Nucleon QE Scattering

NEUTRINO REACTIONS AT ACCELERATOR ENERGIES *

C.H. LLEWELLYN SMITH

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

Received 30 August 1971

Possible investigations of the properties of weak interactions using high energy neutrinos are reviewed. The use of neutrinos to probe hadron structure is discussed.

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.

Formalism describing QE scattering from FREE nucleons included in review article by Llewellyn Smith in 1971

The CCQE Formalism – Form Factors

squared
4-momentum
transfer to
nucleon

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2 \theta_C}{8\pi E_\nu^2} \times \left[A(Q^2) \mp \frac{(s-u)B(Q^2)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^2} \right]$$

- A, B, and C are functions of different form factors which parameterize weak charge distributions in the nucleon

$$A(Q^2) = \frac{m_\ell^2 + Q^2}{M^2} [(1+\tau)|F_A|^2 - (1-\tau)|F_1^V|^2 + \tau(1-\tau)|F_2^V|^2 + 4\tau F_1^V F_2^V] \\ - \frac{m_\ell^2 + Q^2}{M^2} \frac{m_\ell^2}{M^2} [|F_1^V + F_2^V|^2 + |F_A + 2F_P|^2 - 4(1+\tau)F_P^2]$$

$$B(Q^2) = 4\tau F_A (F_1^V + F_2^V) \quad C(Q^2) = \frac{1}{4} (|F_A|^2 + |F_1^V|^2 + \tau|F_2^V|^2)$$

$$F_1^V(Q^2) = \frac{G_E^V(Q^2) + \tau G_M^V(Q^2)}{1 + \tau}$$

$$\tau = \frac{Q^2}{4M^2} \quad F_2^V(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1 + \tau}$$

$$F_A(Q^2) = \frac{F_A(0)}{(1 + Q^2/M_A^2)^2}$$

$$G_E^V(Q^2) = G_E^p(Q^2) - G_E^n(Q^2)$$

$$G_M^V(Q^2) = G_M^p(Q^2) - G_M^n(Q^2)$$

Brief Summary

2 Vector Form Factors (F_1 , F_2)

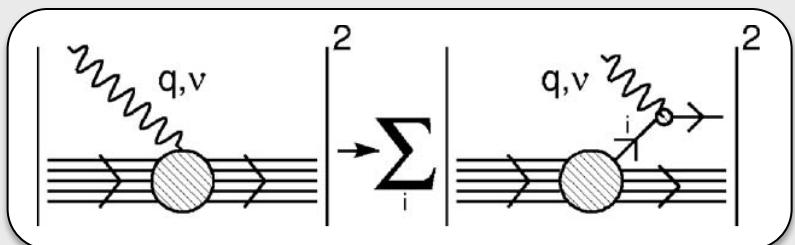
1 Axial-Vector Form Factor (F_A)

electrons and neutrinos

neutrinos only

Relativistic Fermi Gas For Nucleus

- Working on nuclear models for neutrino scattering can take you far!
- In the *Impulse Approximation*, scatter off independent single nucleons incoherently summed over all nucleons in the nucleus



- If we further assume the *nucleon at rest*, we can determine E_ν and Q^2 from the lepton kinematics alone

$$E_\nu^{QE} = \frac{2(M_n - E_B) E_\ell - [(M_n - E_B)^2 + m_\ell^2 - M_p^2]}{2[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

$$Q_{QE}^2 = -m_\ell^2 + 2E_\nu^{QE} \left(E_\ell - \sqrt{E_\ell^2 - m_\ell^2} \cos(\theta_\ell) \right)$$

Pretty handy!



NEUTRINO REACTIONS ON NUCLEAR TARGETS [‡]

R. A. SMITH [#] and E. J. MONIZ ^{##}

Institute of Theoretical Physics, Department of Physics,
Stanford University, Stanford, California 94305

with energies lowered from free particle energies by an average nuclear potential. Although this choice of wave functions corresponds to a nucleus without detailed structure, the dominant features of the nuclear cross section are consistently represented.

Smith, R. A., and E. J. Moniz, 1972, Nucl. Phys. B43, 605.

M_n = neutron mass
 M_p = proton mass
 E_B = separation energy
 m_ℓ = lepton mass
 E_ℓ, θ_ℓ = lepton energy and angle

Historical Approach To QE Scattering

- Basic strategy was the following:

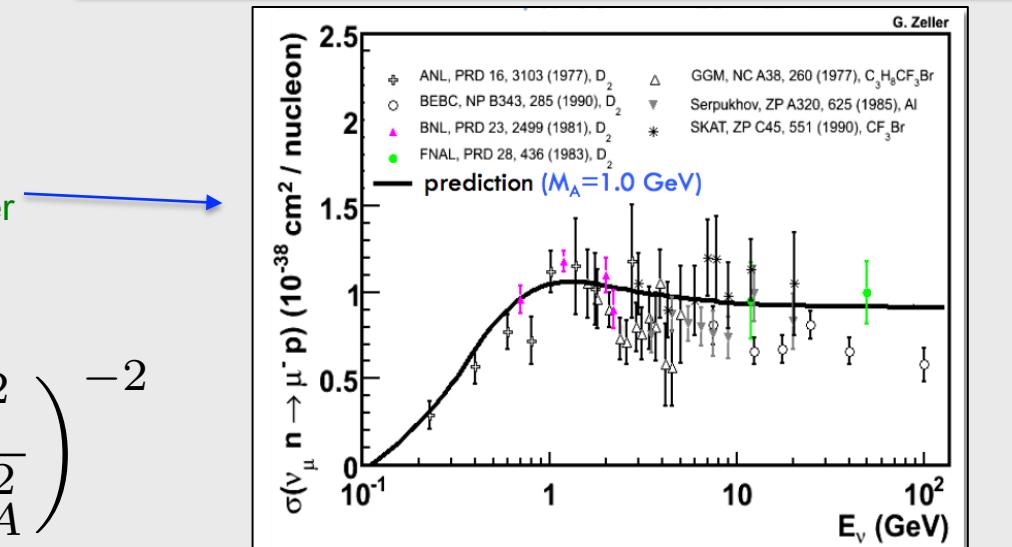
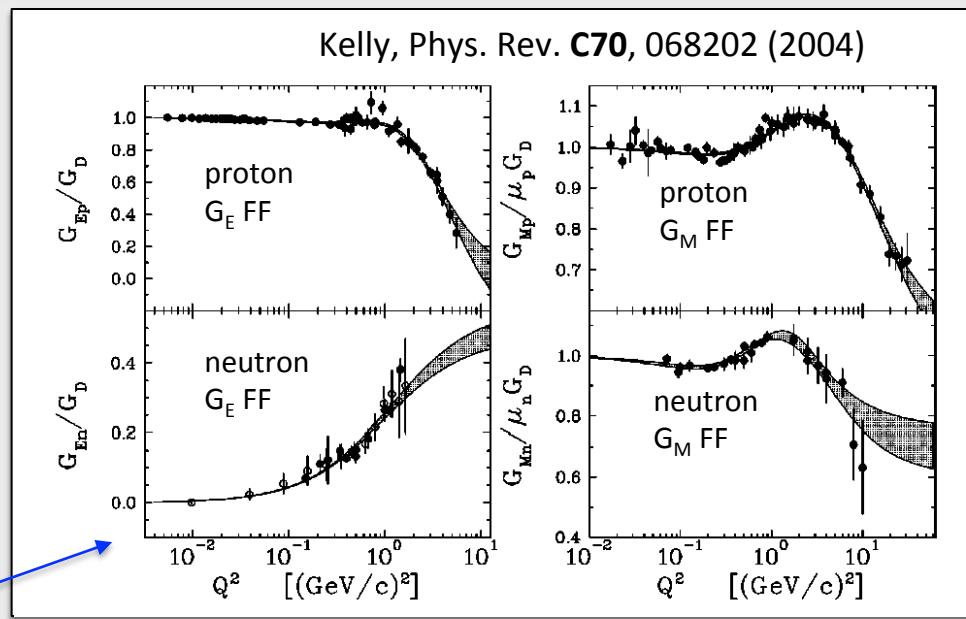
- Start with Llewellyn Smith formalism and assume Relativistic Fermi Gas (RFG) for nucleus

- Weak charge Form Factors measured by experiment

- Vector Form Factors measured in electron scattering

- Assume a dipole form for the Axial-Vector Form Factor and use neutrino CCQE scattering data to determine the axial mass parameter

$$F_A(Q^2) = F_A(0) \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

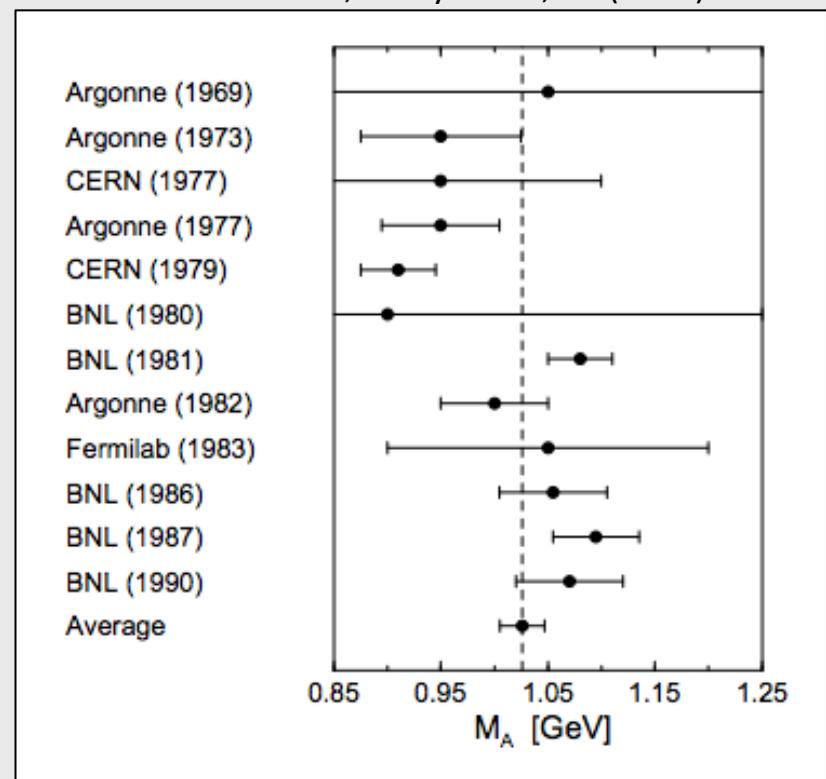


Historical Approach To QE Scattering

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Bernard *et al.*, J. Phys. **G28**, R1 (2002)

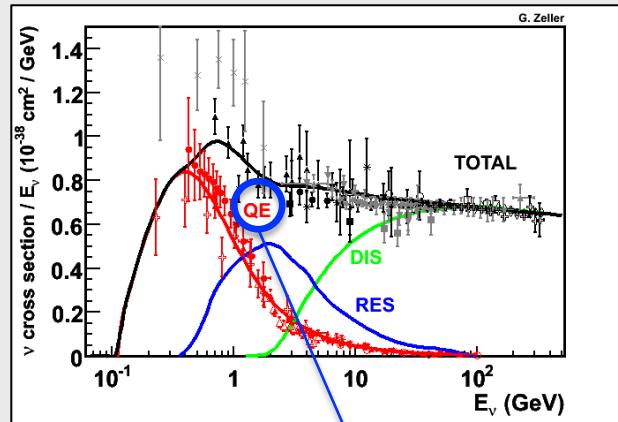


$$M_A \approx 1.0 \text{ GeV}/c^2$$

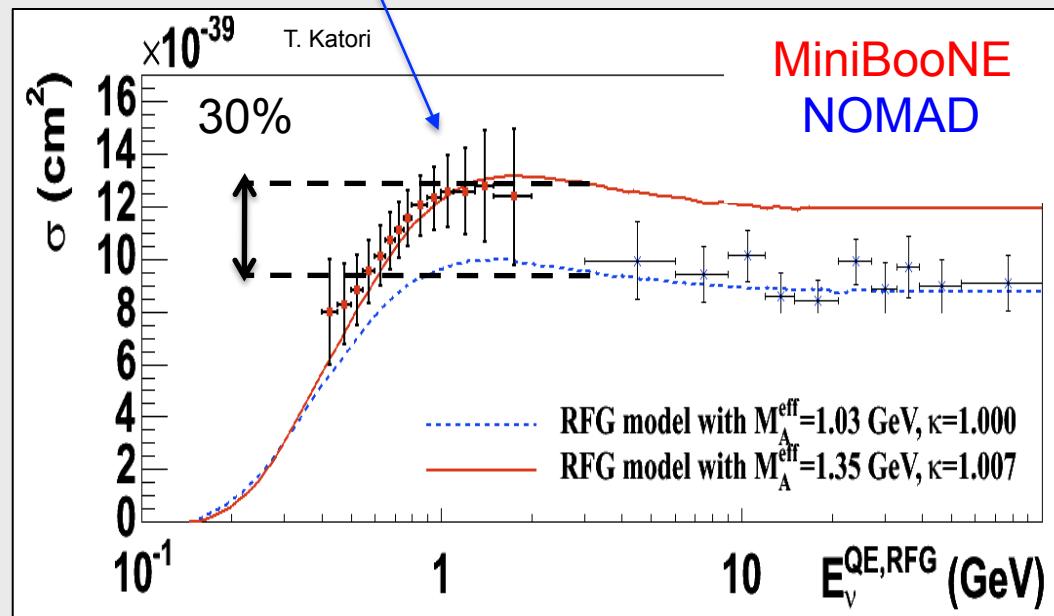
$$F_A(Q^2) = F_A(0) \left(1 + \frac{Q^2}{M_A^2} \right)^{-2}$$

Voilà,
model complete!

But Is It Good Enough?



With modern, *high statistics* data on heavier targets (carbon) and improved flux predictions, one finds tension between data sets and this model



$$F_A(Q^2) = F_A(0) \left(1 + \frac{Q^2}{M_A^2} \right)^{-2}$$

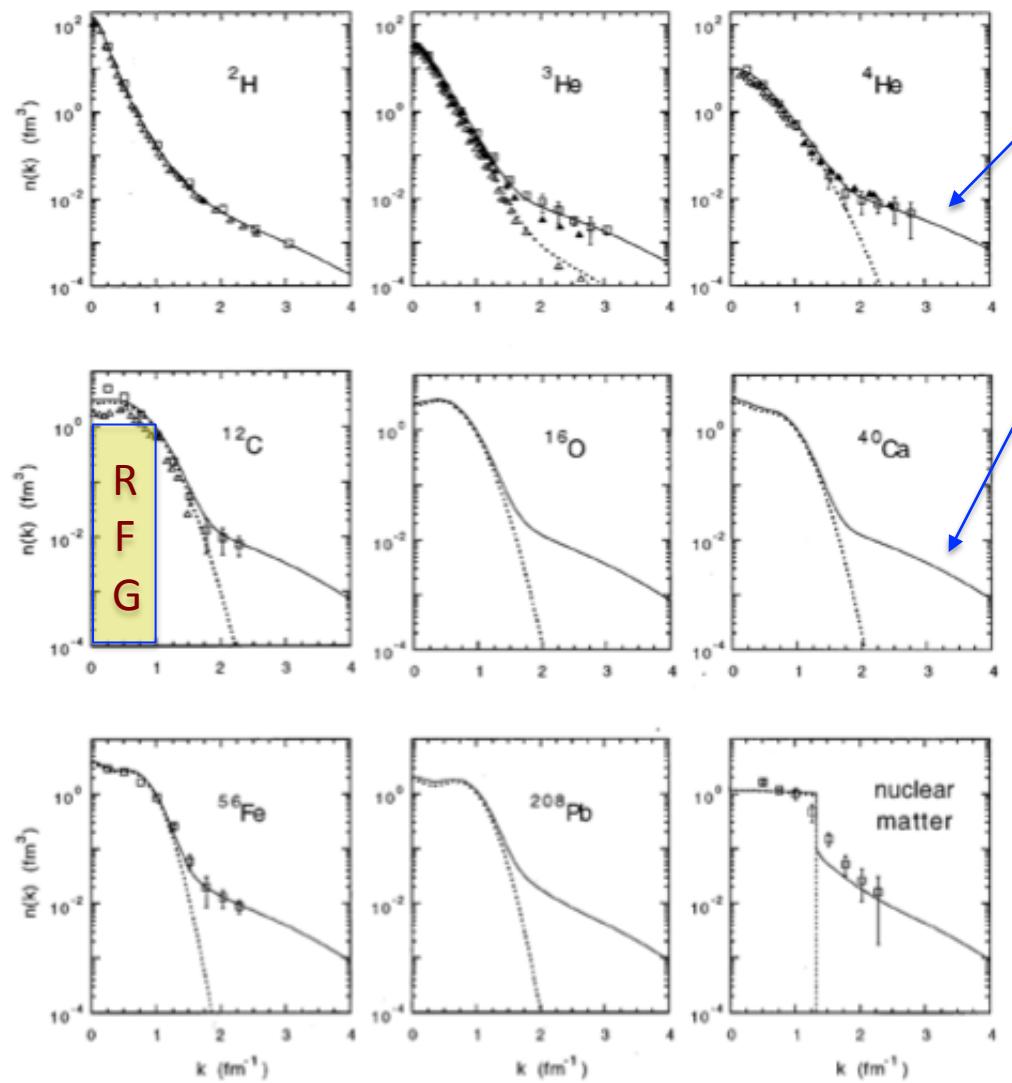
Increase M_A , the free parameter in the **axial-vector FF??**

But Is It Good Enough?

- Both theory and experimental hints tell us that it is not
- Nucleon-nucleon interactions and 2-body currents are ignored
 - For $A \geq 12$ *short range correlations (SRC)* affect ~20% of nucleons
 - These can lead to a nucleon momentum well above the Fermi sea cutoff
 - Correlated nucleon(s) may be ejected when its partner is scattered by an electron or neutrino
 - This change on the hadronic side of the interaction impacts the kinematics and spoils your neutrino energy estimation
 - Other correlations are predicted as well, such as *meson exchange currents (MEC)* which may enhance part of the cross section significantly
 - Again, multi-nucleon emission and impacted neutrino energy reconstruction are consequences

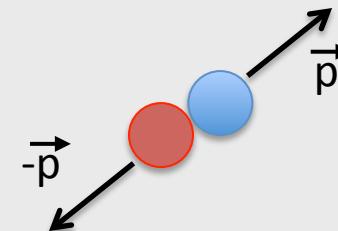
Momentum Distributions In Nucleus

J. Arrington et al., arXiv:1104.1196 [nucl-ex]



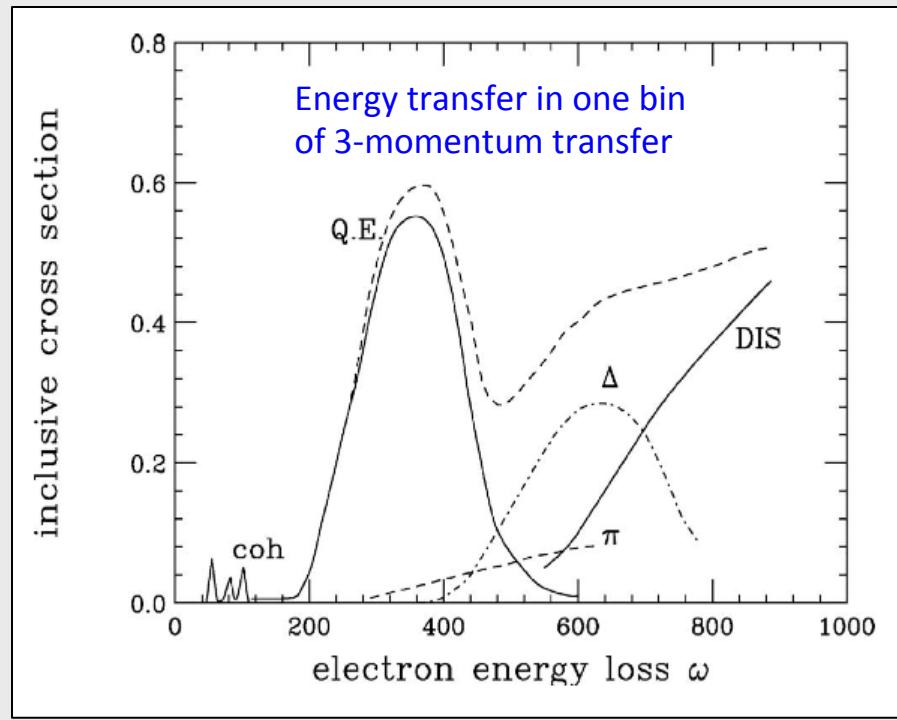
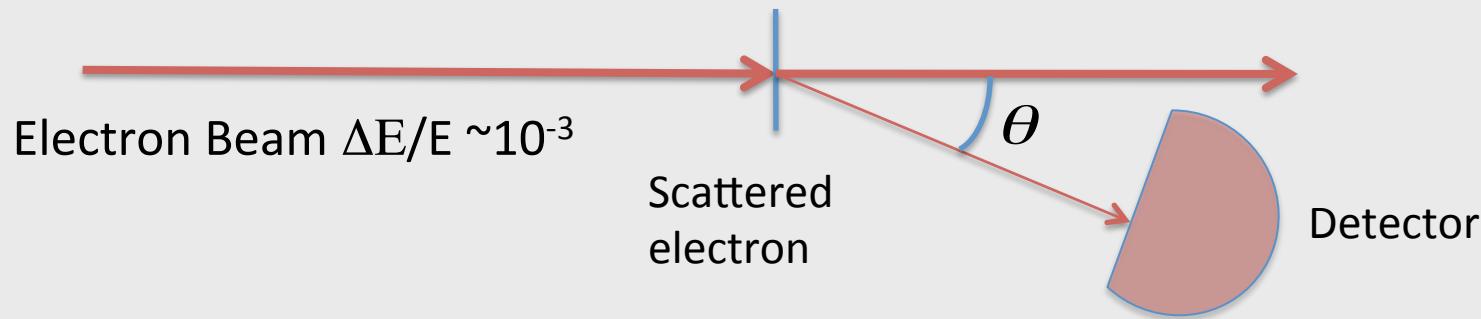
Note the high momentum tails look like deuteron

- High momentum tails result of short range correlations
- This correlation is neglected when treating the nucleus as a collection of free nucleons



Electron Scattering

- Impact of correlations seen in *electron scattering* data



Initial electron energy precisely known. Scattered electron angle and energy well measured. Can know energy and momentum transferred to the nucleus very precisely without measuring hadron final state.

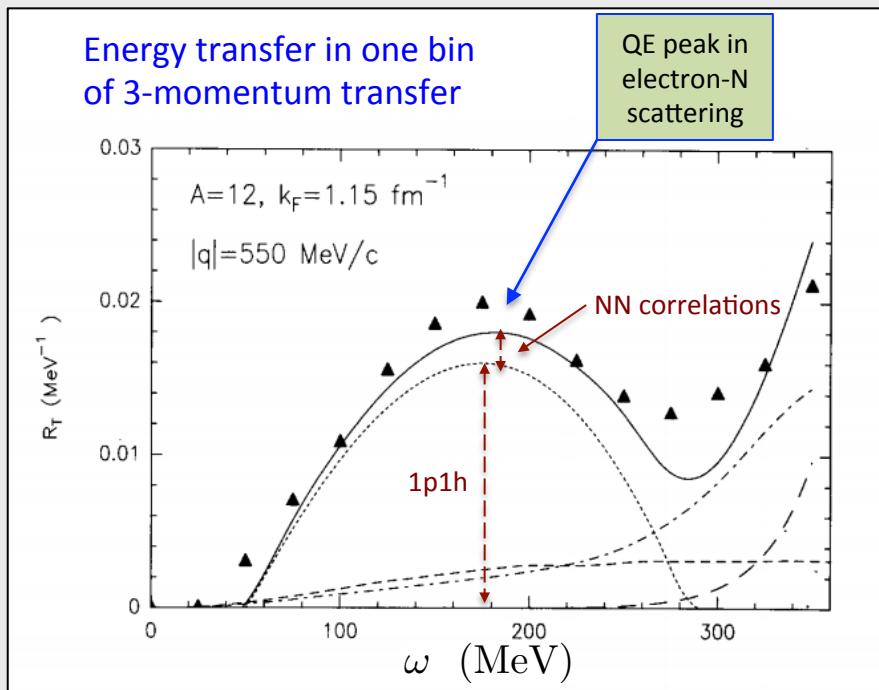
$$\frac{d^2\sigma}{d\Omega d\omega} = \Gamma [R_T(q, \omega) + \epsilon \cdot R_L(q, \omega)]$$

Separate cross section into “longitudinal” and “transverse” components. Polarization of virtual photon.

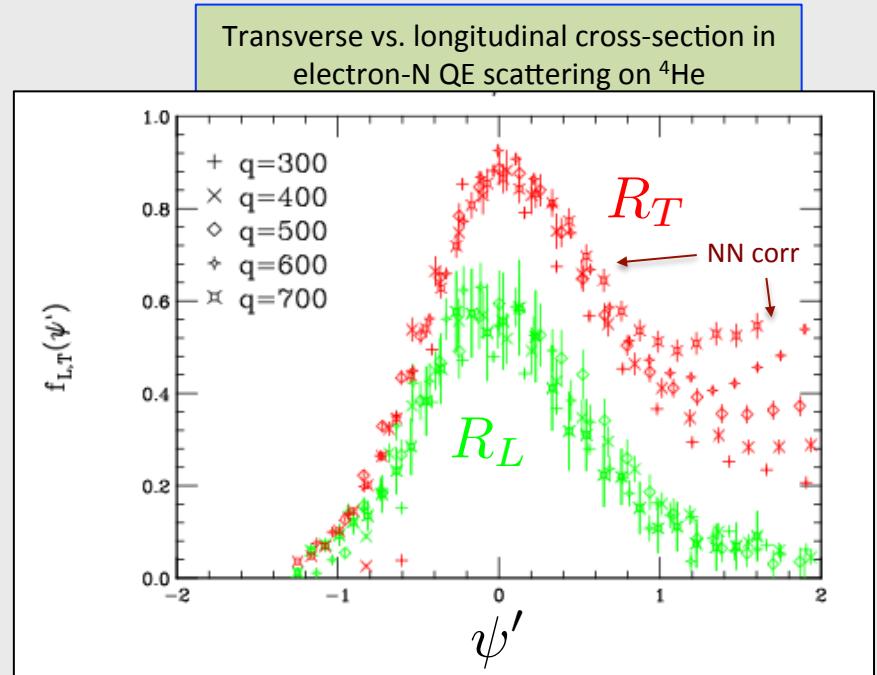
$R_L = R_T$ for RFG of independent nucleons

Transverse and Longitudinal Strength

- Impact of correlations seen in *electron scattering* data



Dekker et al. PLB 266, 249 (1991)



J. Carlson, et al., PRC 65, 024002 (2002)

ω = energy transfer to nucleus

q = 3-momentum transfer to nucleus

ψ' = scaling variable $\psi'(\omega, q)$

$$\psi' = \frac{\sqrt{\omega^2 + 2M\omega} - q}{k_F}$$

$R_L = R_T$ for RFG of independent nucleons

NN Correlations in Neutrino Scattering

- Recent attempts to model these effects in neutrino scattering

- Martini et al. PRC 80, 065001 (2009)
- Martini, Ericson, Chanfray, Marteau, PR C81, 045502 (2010)
- Amaro, Maieron, Barbaro, Caballero, Donnelly, PR C82, 046601 (2010)
- Benhar, arXiv:1012.2032
- Alvarez-Ruso, arXiv:1012.3871
- Amaro, Barbaro, Caballero, Donnelly, arXiv:1012.4265
- Nieves, Ruiz Simo, Vicente Vacas, PR C83, 045501 (2011)
- Fernandez-Martinez, Meloni, PL B697, 477 (2011)
- Amaro, Barbaro, Caballero, Donnelly, Williamson, PL B696, 151 (2011)
- Ankowski, Benhar, arXiv:1102.3532
- Meucci, Caballero, Giusti, Udias, arXiv:1103.0636
- Benhar, Veneziano, arXiv:1103.0987
- Amaro, Barbaro, Caballero, Donnelly, Udias, arXiv:1104.5446
- Antonov, Ivanov, Caballero, Barbaro, Udias, Guerra, Donnelly, arXiv:1104.0125

A partial list of recent calculations

Models are *qualitatively similar*, though not *quantitatively identical*

Are effects identical for *electrons vs. neutrinos?*

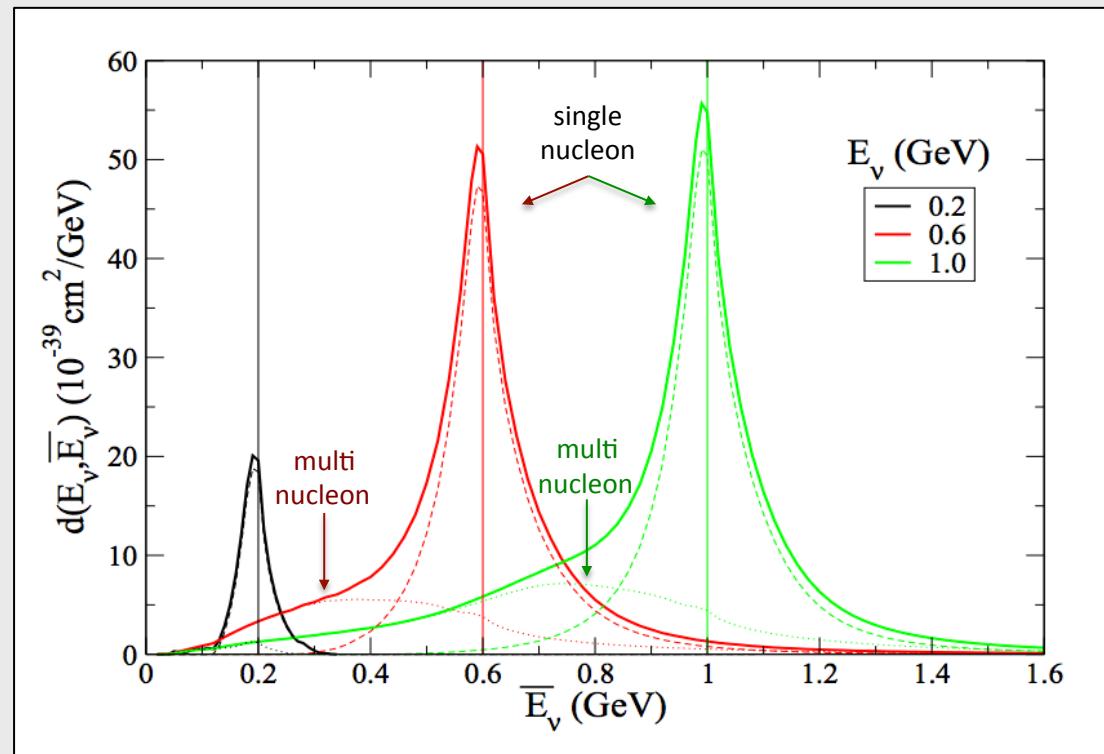
Different for ν and $\bar{\nu}$?

Understand implications for *neutrino energy* reconstruction

Possible Impact For Neutrino Experiments

- Recall, formula to the right assumes independent nucleon
- Use of the formula when striking a *correlated nucleon* can be quite wrong
- Even calorimetric reconstruction is challenged since the MC does not simulate the hadronic side of the interaction properly in these events
- Recall, up to *20-30% of the events off correlated pairs*

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\ell - [(M_n - E_B)^2 + m_\ell^2 - M_p^2]}{2[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

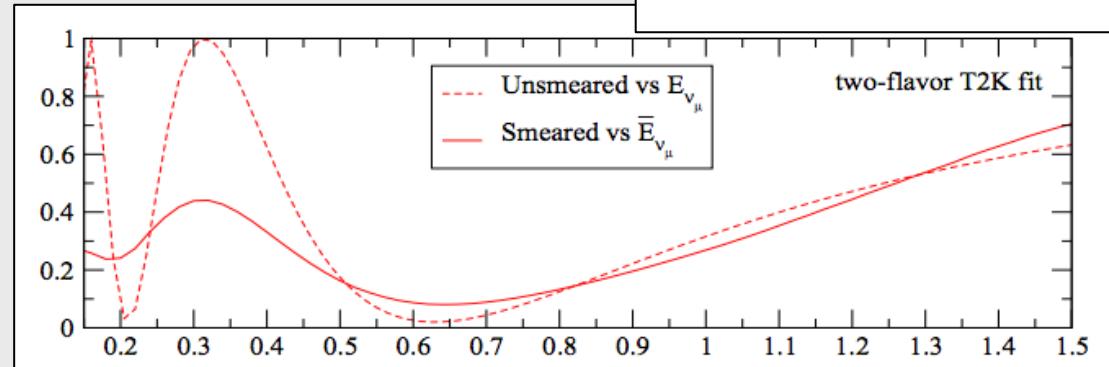
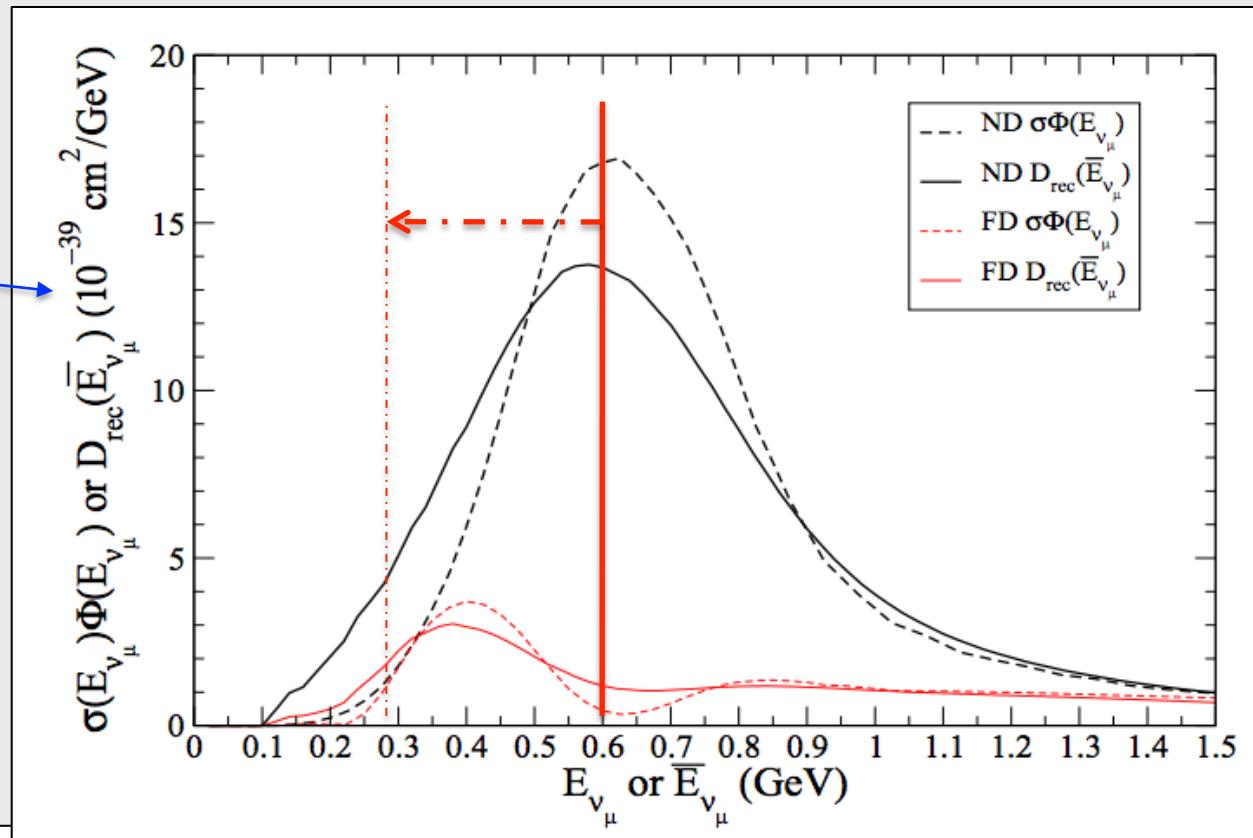


Martini et al. arXiv:1211.1523

Also: J. Sobczyk arXiv:1201.3673,
Lalakulich et al. arXiv:1208.3678,
Nieves et al. arXiv:1204:5404

Possible Impact For Neutrino Experiments

In this analysis they go on to show examples using T2K and MiniBooNE expected event distributions

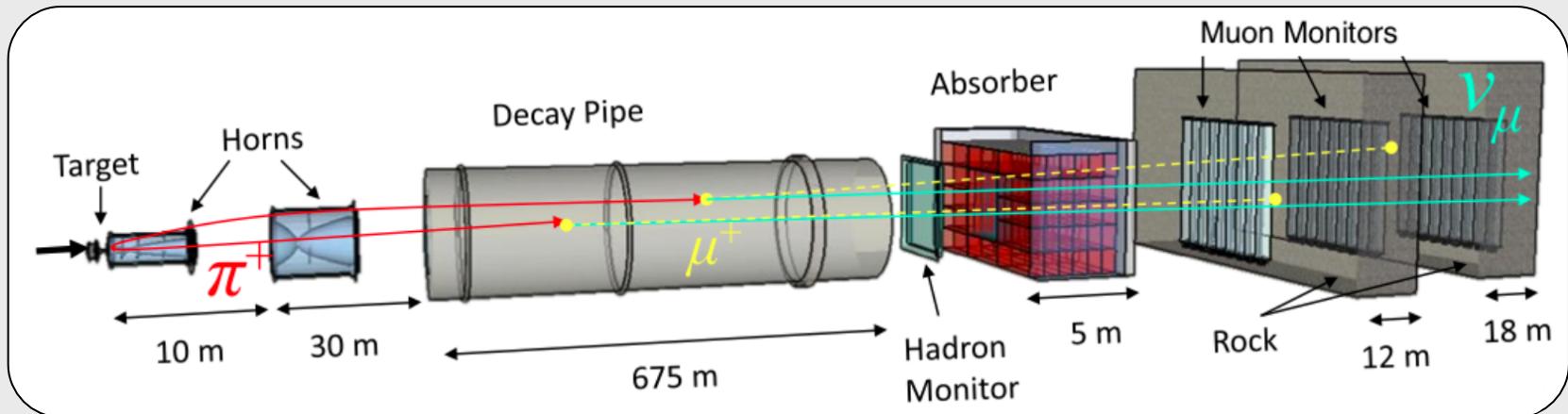


Martini et al. arXiv:1211.1523

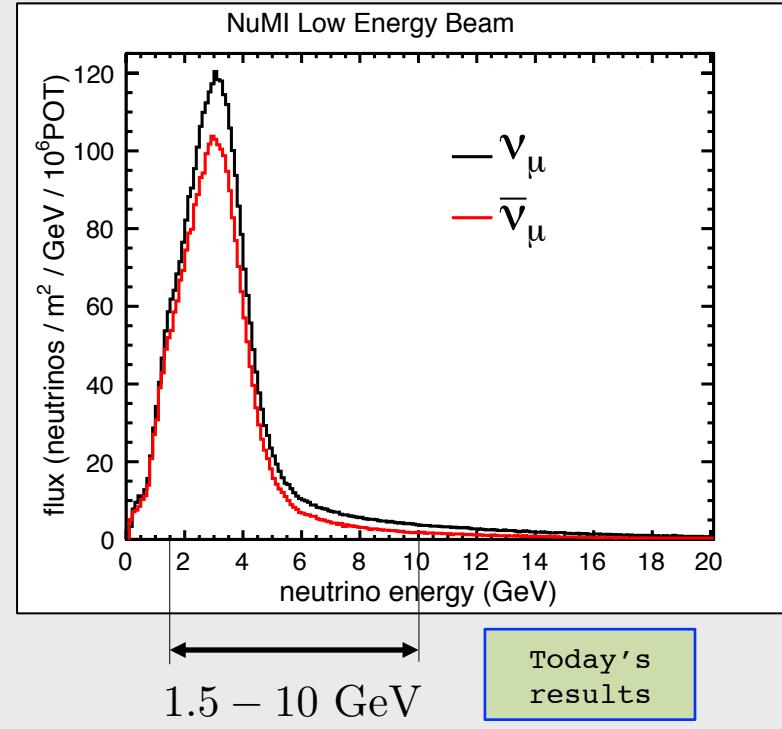
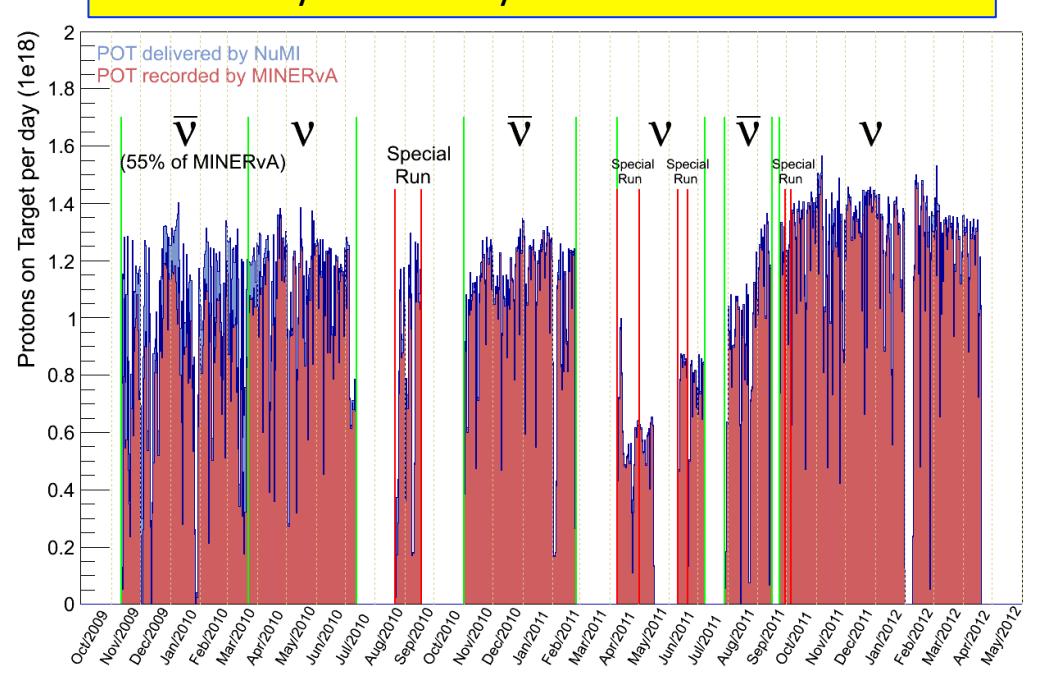
Osc to No-osc Ratio

The MINERvA Experiment

The NuMI Beam



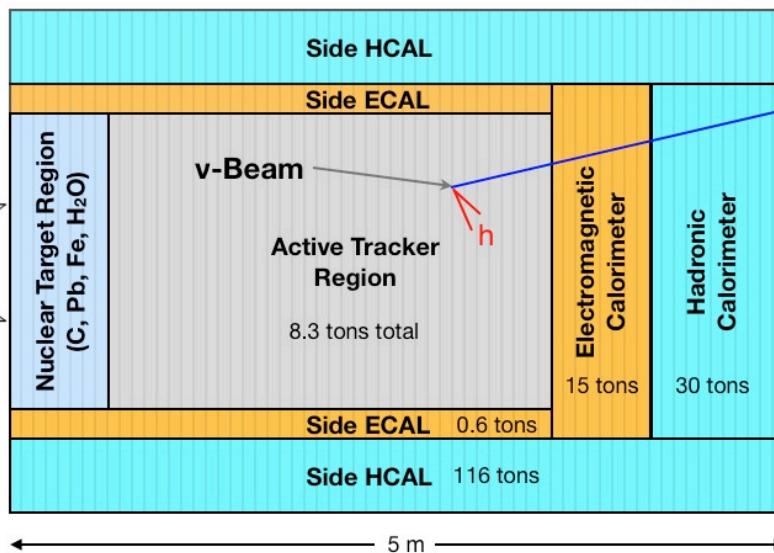
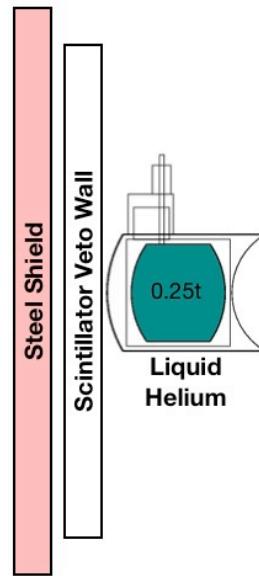
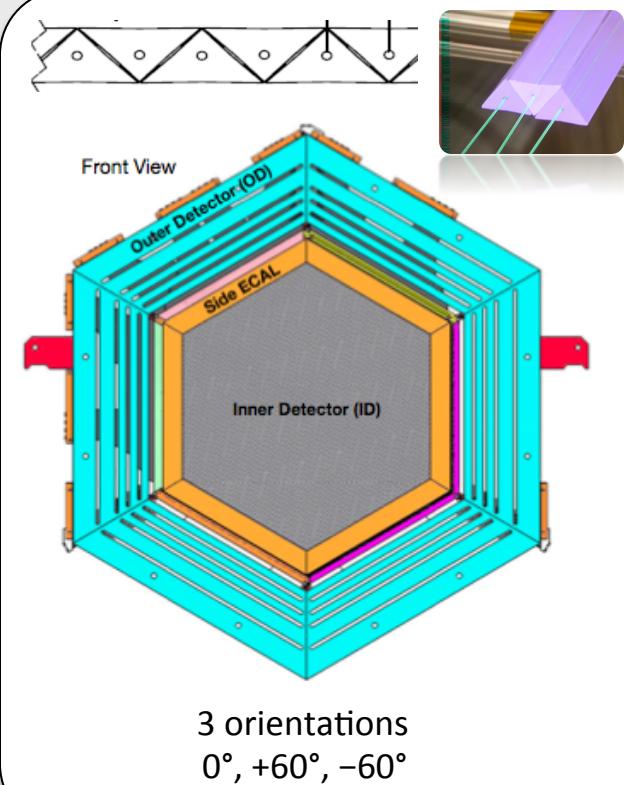
Thank you for the years of intense beam!!





MINERvA

Thank you to MINOS for the generous sharing of their Near Detector data!!



Detector comprised of **120 “modules”** stacked along the beam direction

Central region is **finely segmented scintillator tracker**

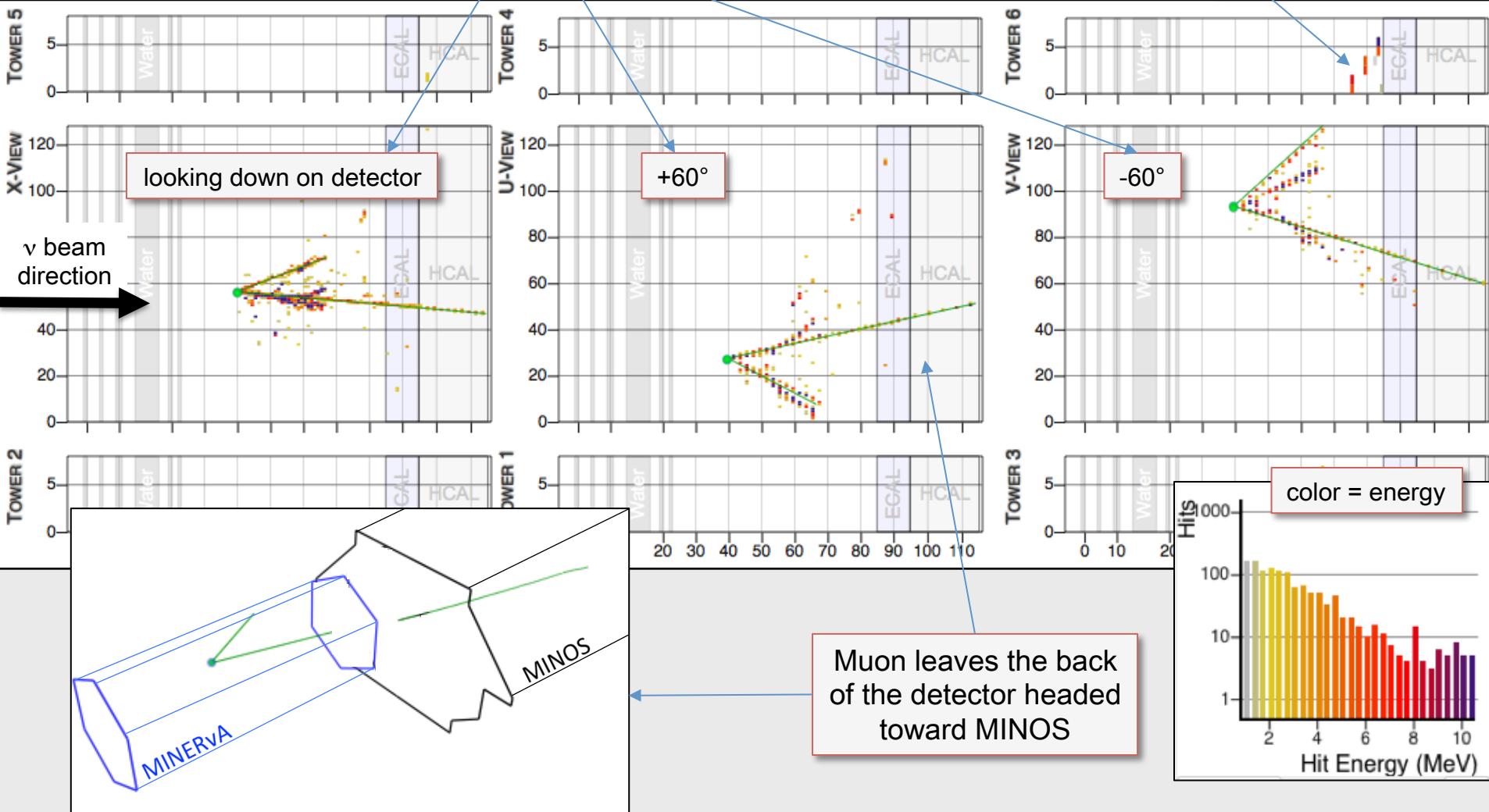
~32k plastic scintillator strip channels total



MINERvA

Particle leaves the inner detector, stops in outer iron calorimeter

3 stereo views, X—U —V, shown separately





More than just a detector...

~80 collaborators from particle and nuclear physics

University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago

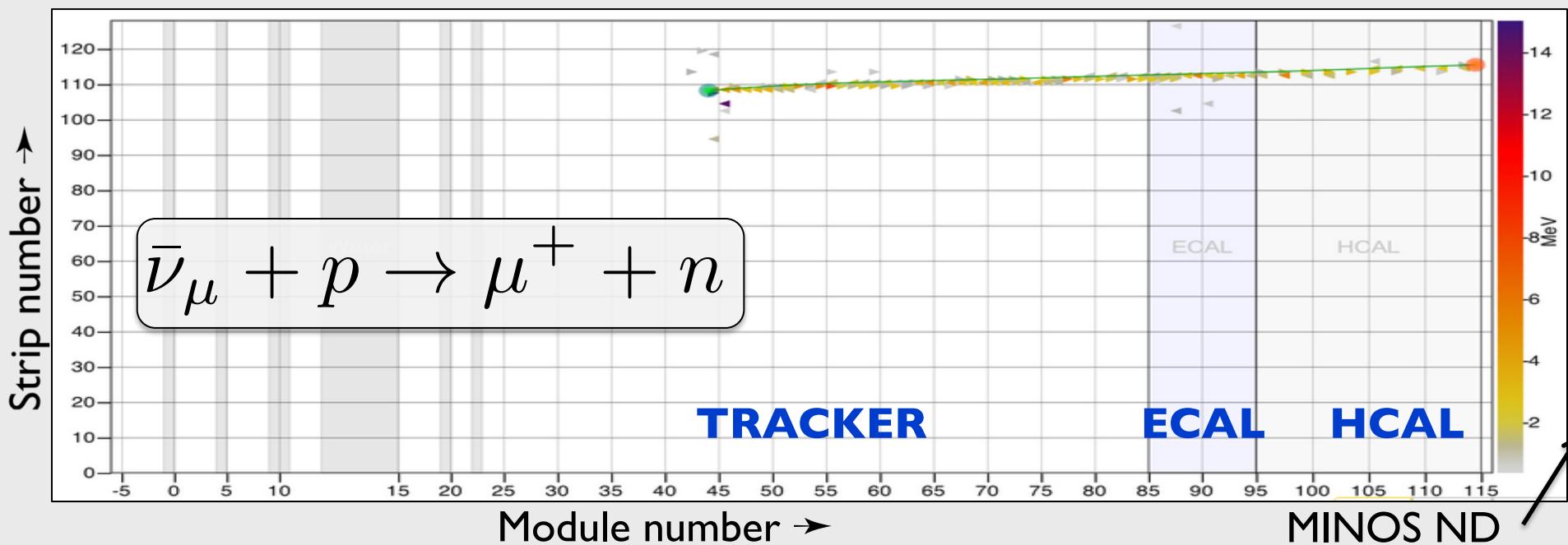
Otterbein University
Pontificia Universidad Católica del Perú
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary



Isolating QE Events

v Beam →

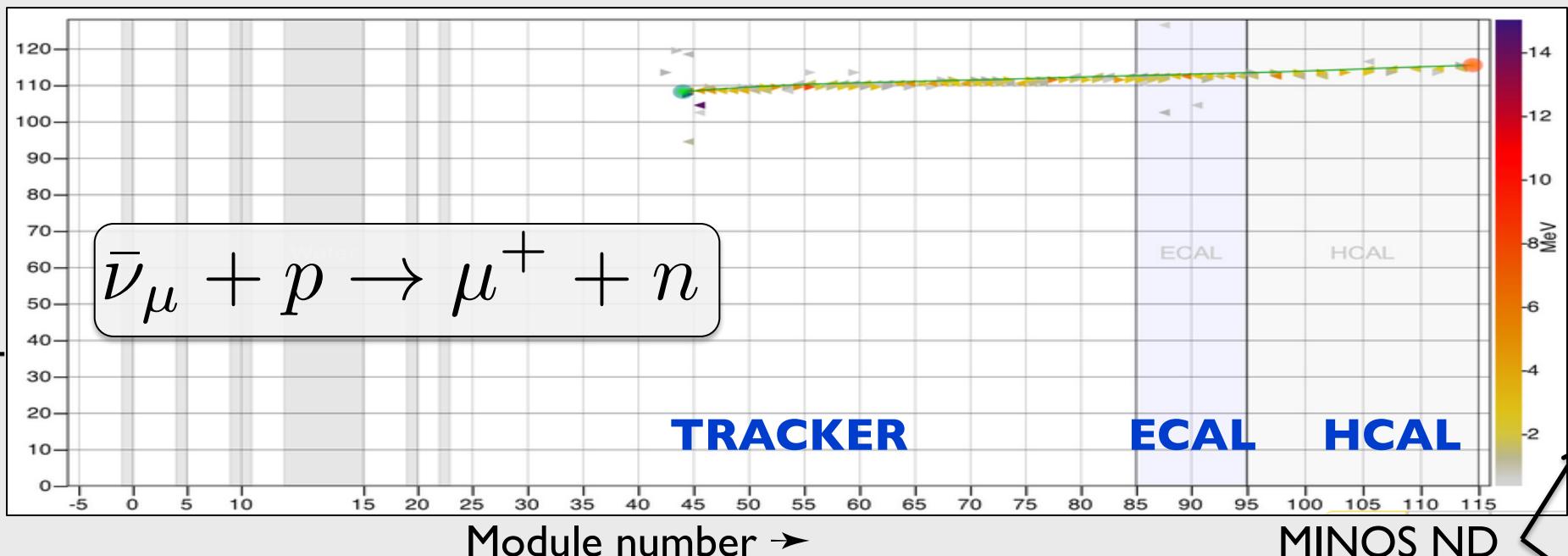
MeV



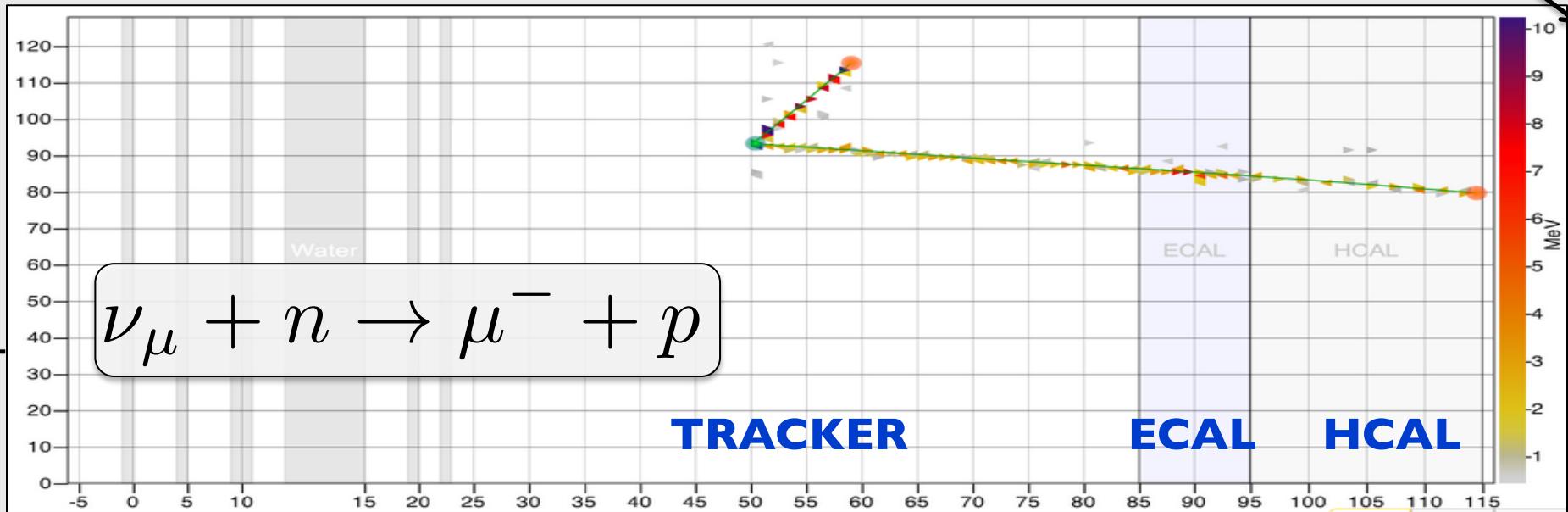
ν Beam 

MeV

Strip number →



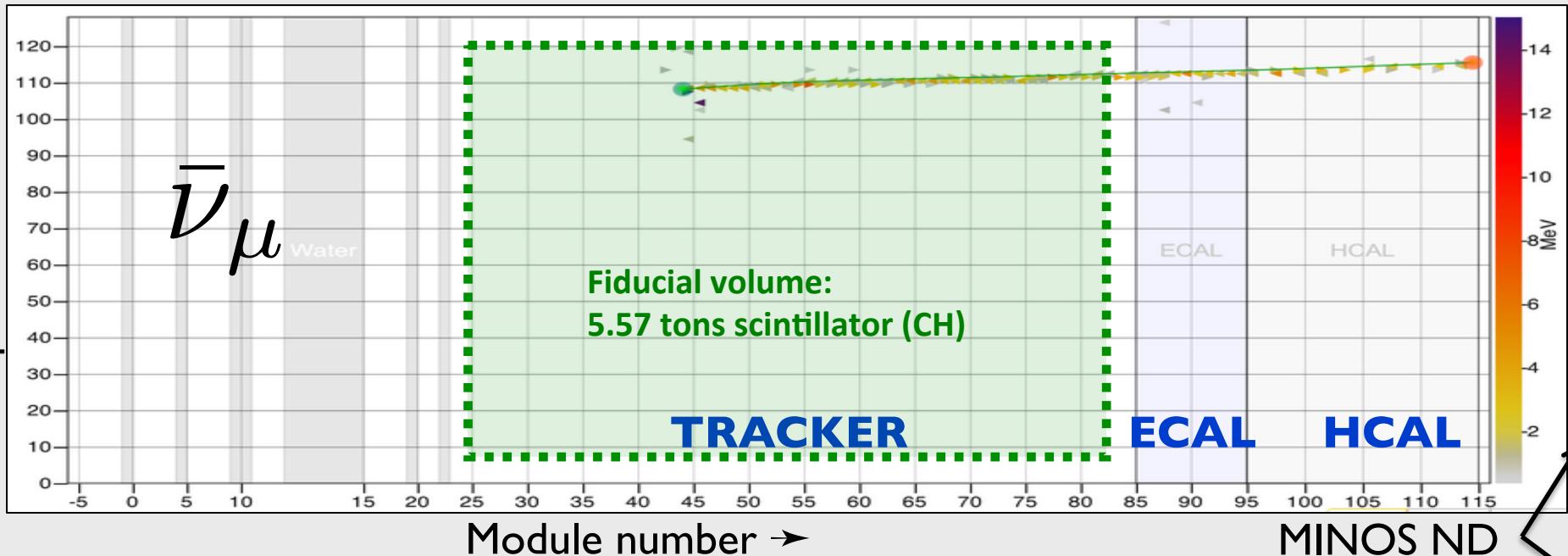
Strip number →



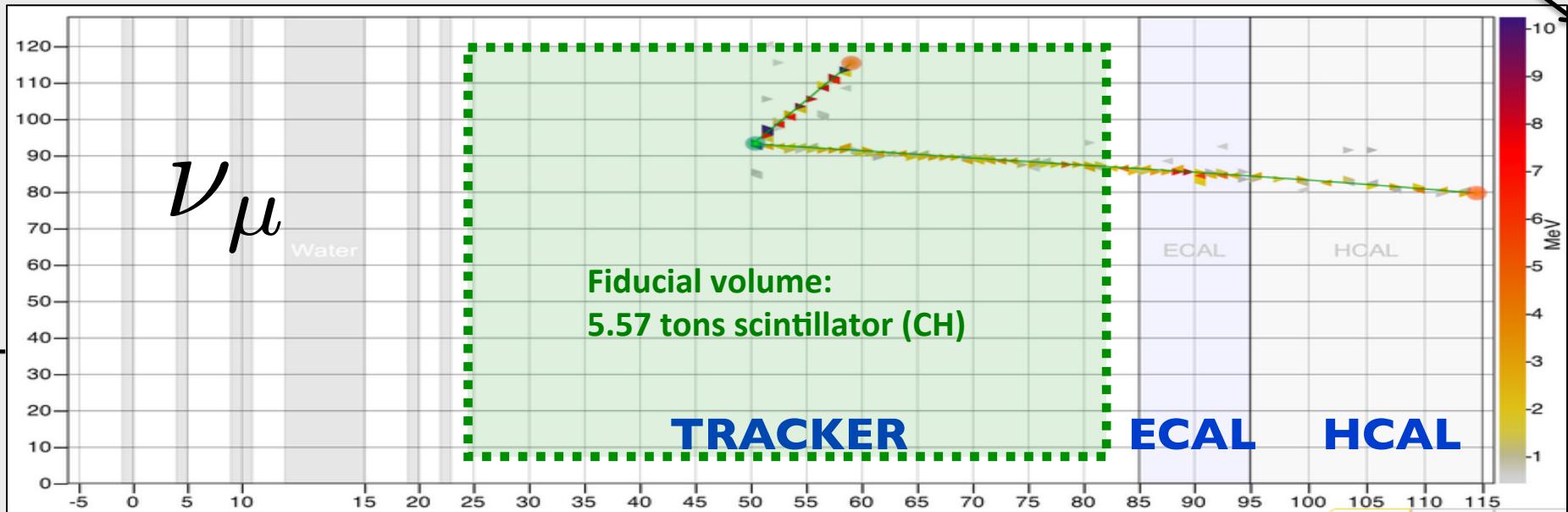
ν Beam 

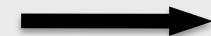
MeV

Strip number \rightarrow



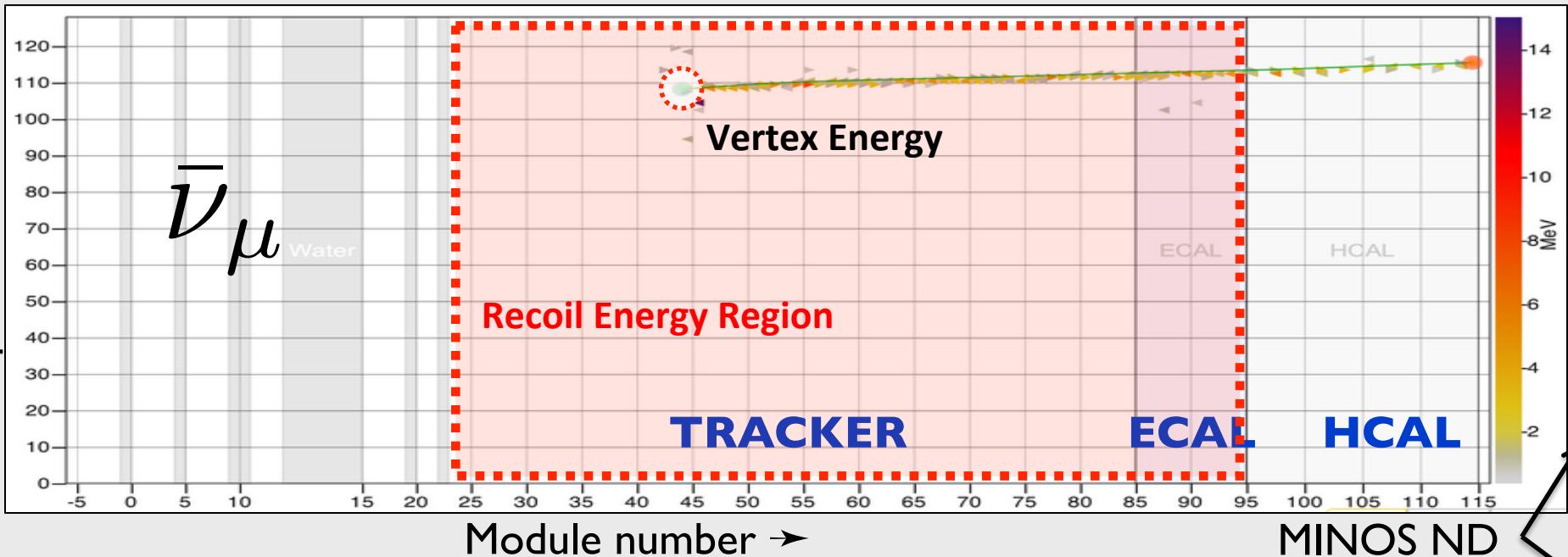
Strip number \rightarrow



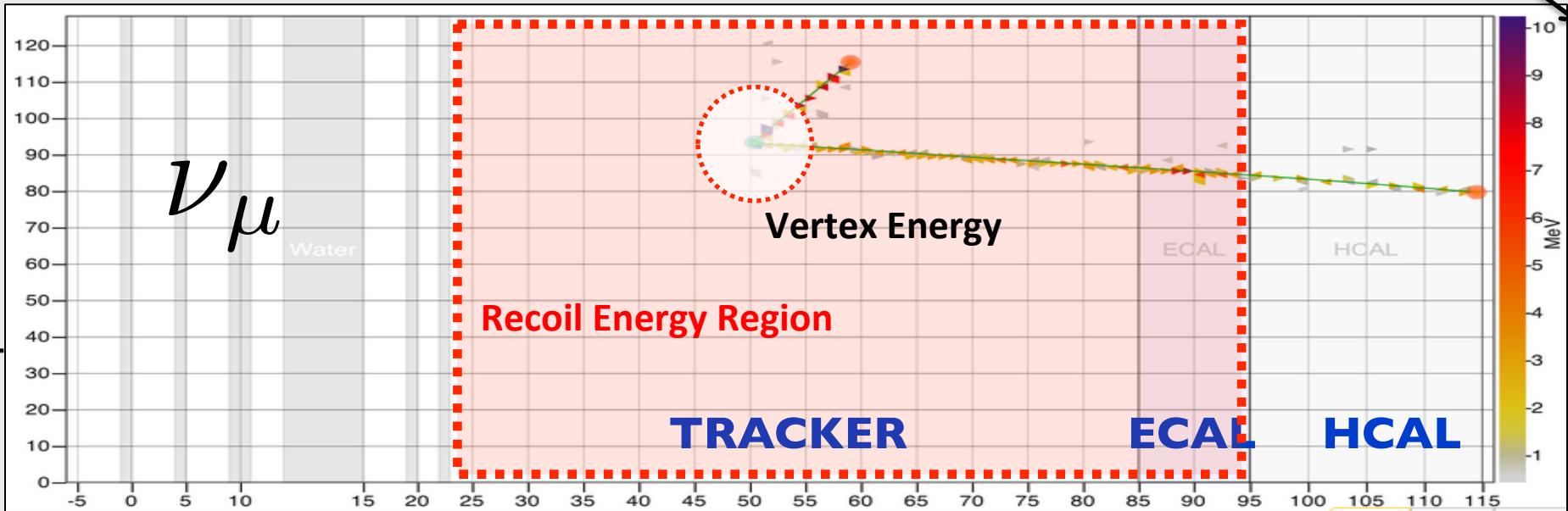
ν Beam 

MeV

Strip number \uparrow

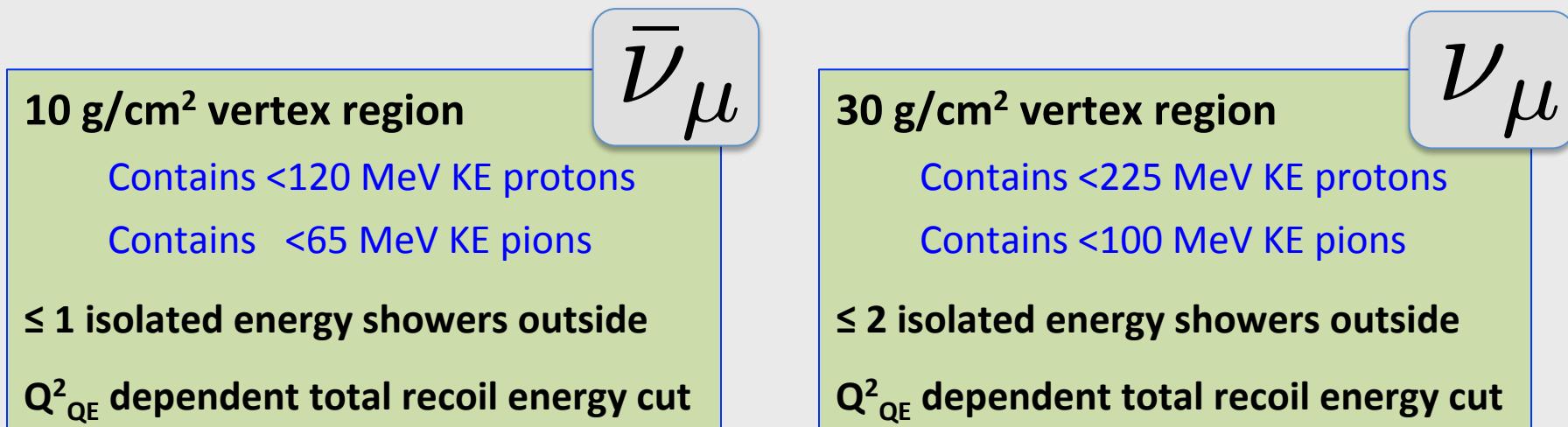


Strip number \uparrow



QE Event Selection

1. Muon track matched to MINOS track, *momentum and charge analyzed*
 - μ^+ for antineutrino
 - μ^- for neutrino
2. Recoil energy is summed in the tracker and ECAL *excluding a region immediately around the interaction vertex* (determined by the muon track)
 - This excluded region limits sensitivity to the modeling of low energy hadrons produced in the interaction (particularly from multi-nucleon effects)



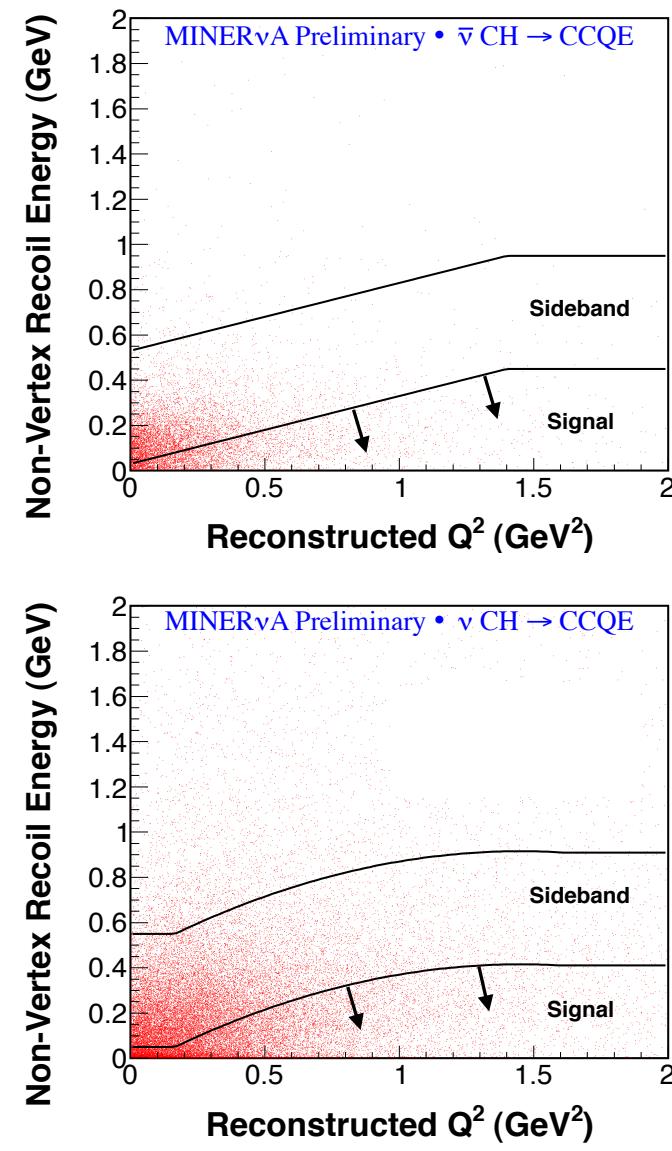
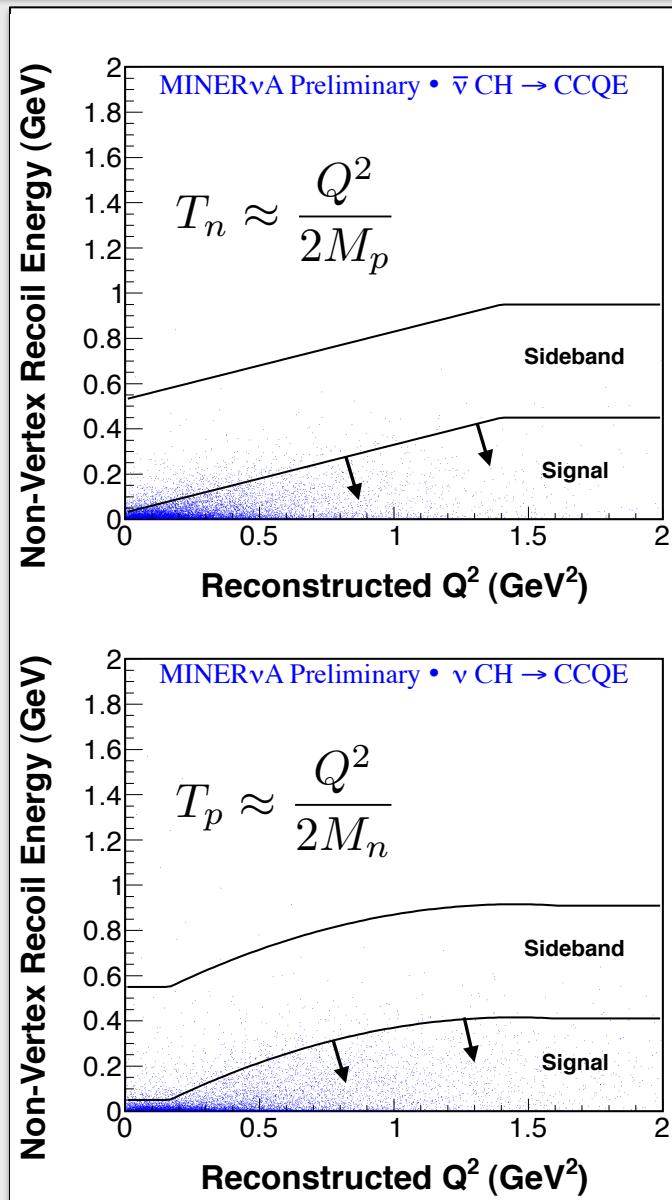
Recoil Energy

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2 \cos \theta_\mu} \right)$$

$\bar{\nu}_\mu$

QE

ν_μ



squared
4-momentum
transfer to
nucleon

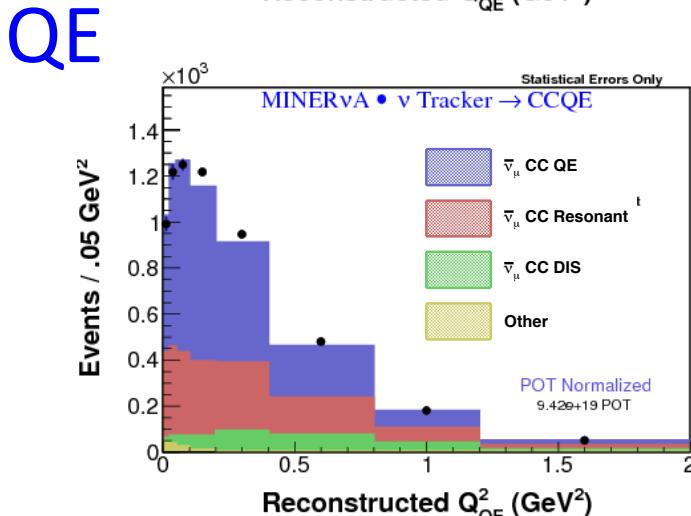
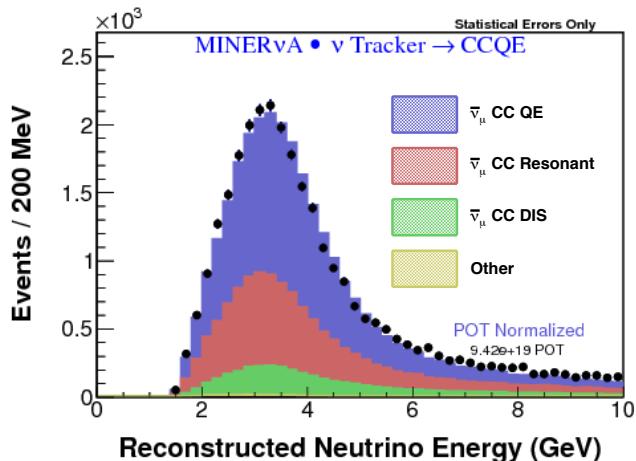
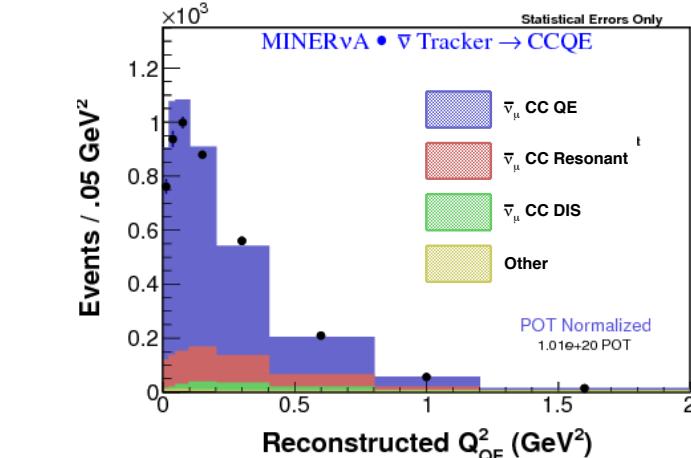
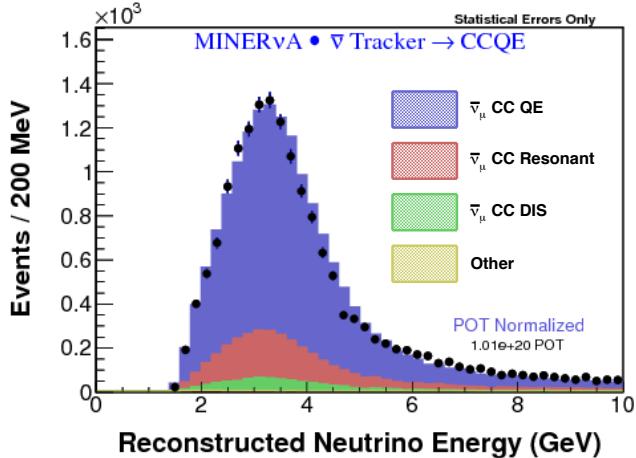


QE Event Candidates

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - [(M_n - E_B)^2 + m_\mu^2 - M_p^2]}{2[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$

$$\frac{d\sigma}{dQ_{QE}^2}$$



$\bar{\nu}_\mu$

16,467 events
54% eff.
77% purity

ν_μ

29,620 events
47% eff.
49% purity

Systematic Uncertainties

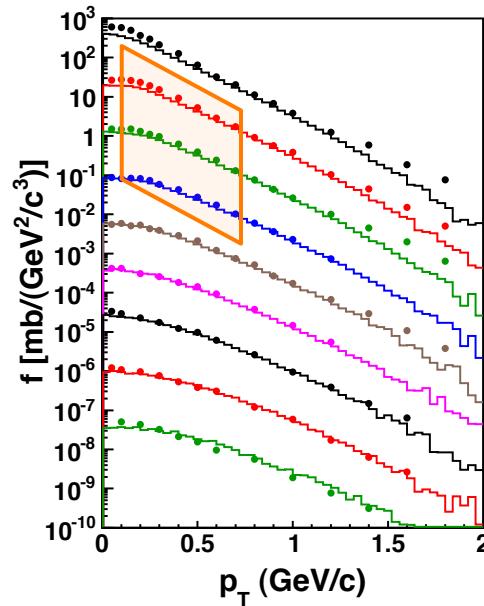
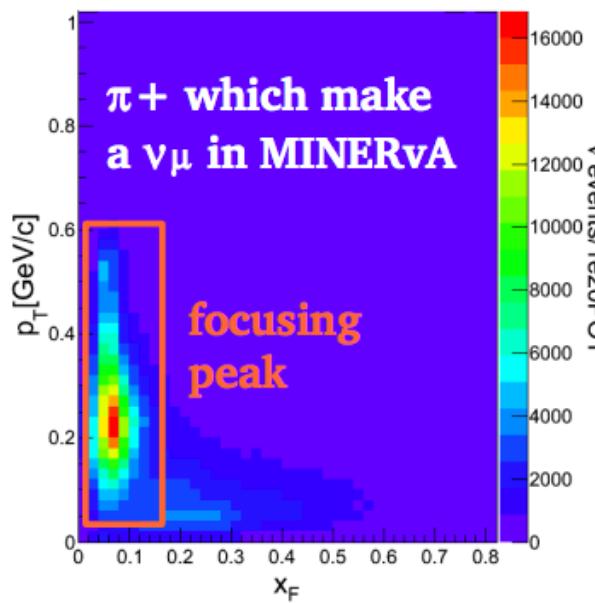
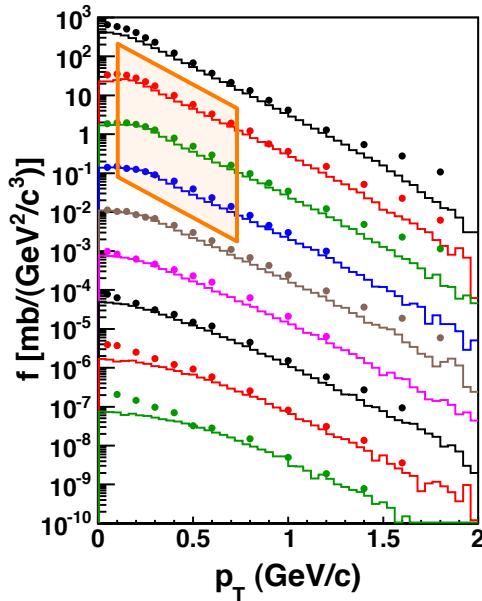
1. Neutrino fluxes
2. Muon reconstruction
3. Recoil reconstruction
4. Primary interaction models
5. Final state interactions

1. Neutrino Fluxes

$$p(158 \text{ GeV}) + C \rightarrow \pi^+$$

NA49: Eur.Phys.J C49, 897-917 (2007)

$$p(158 \text{ GeV}) + C \rightarrow \pi^-$$



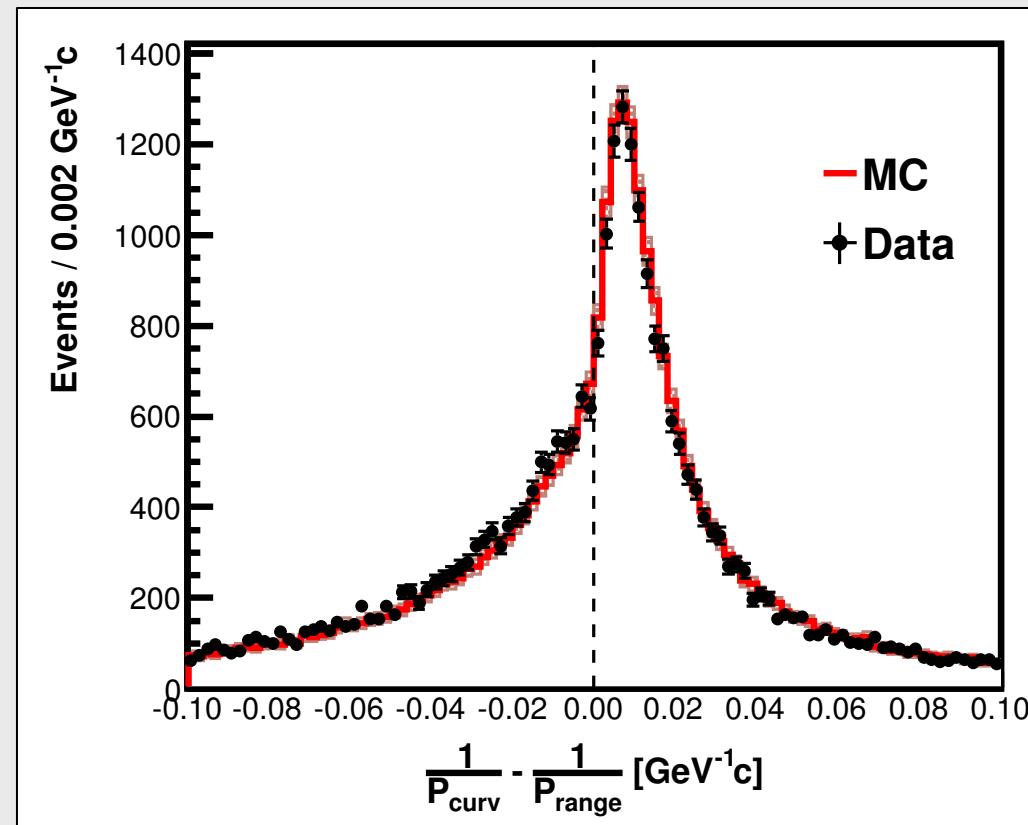
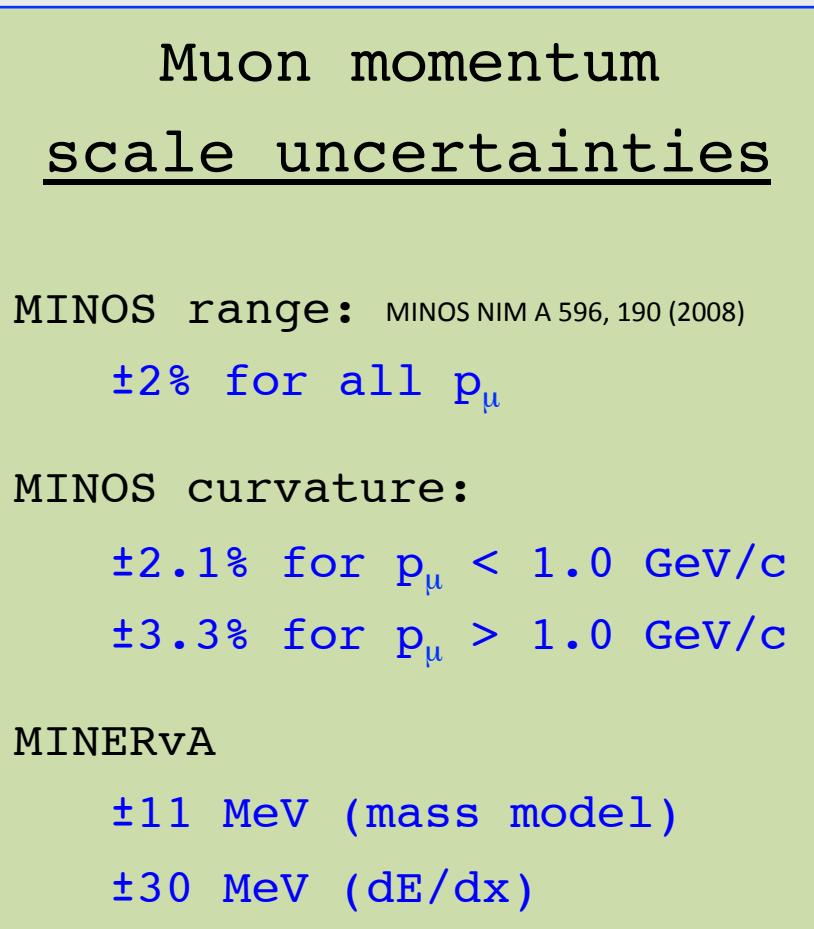
$x_F=0$
 $x_F=0.05 (\times 10^{-1})$
 $x_F=0.10 (\times 10^{-2})$
 $x_F=0.15 (\times 10^{-3})$
 $x_F=0.20 (\times 10^{-4})$
 $x_F=0.25 (\times 10^{-5})$
 $x_F=0.30 (\times 10^{-6})$
 $x_F=0.40 (\times 10^{-7})$
 $x_F=0.50 (\times 10^{-8})$

• • • data
Eur.Phys.J.C. 49,897-917(2007)
— montecarlo
Geant4 Version 9_2_p03

- Monte Carlo reweighted to match measured $\pi^+ \pi^-$ production cross-sections by NA49. Uncertainties from NA49 cross sections propagated directly to flux.
- Use scaling laws to constrain p+C interactions down to 12 GeV proton energy
 - Method tested by scaling to pion production data from NA61 (31 GeV/c) and HARP (12 GeV/c)
- GEANT4 (FTFP_BERT physics model) used for rest of simulation

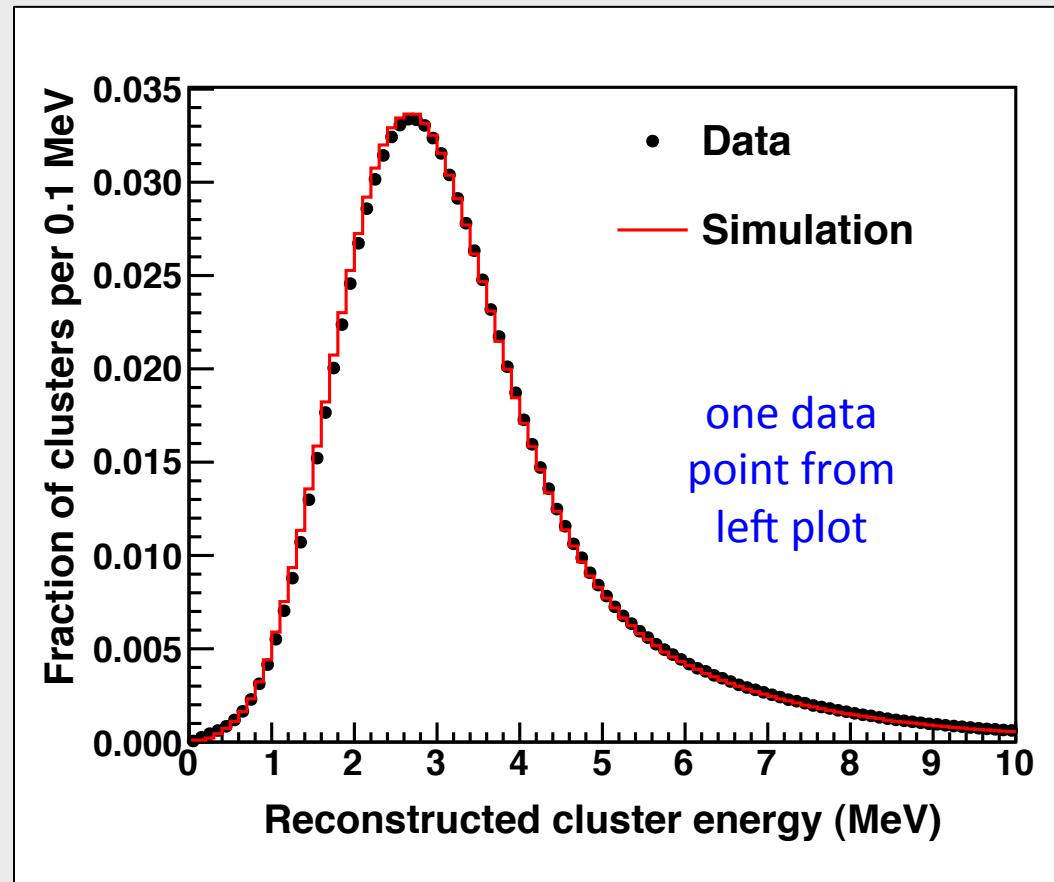
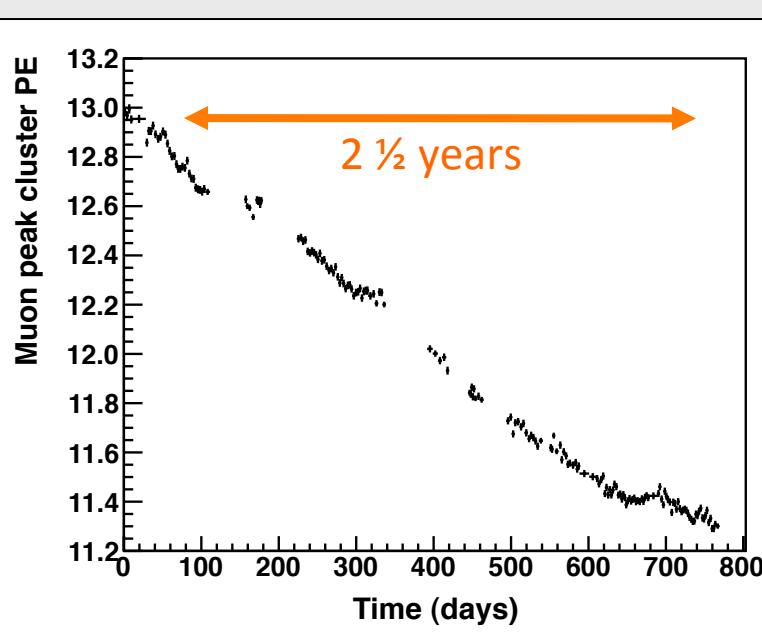
2. Muon Energy Scale

- All muons used in these analyses are momentum analyzed in MINOS ND
 - By range in the steel or by curvature in the magnetic field



3. Recoil Energy Scale

High statistics monitoring of the detector energy response with
"Rock Muons"

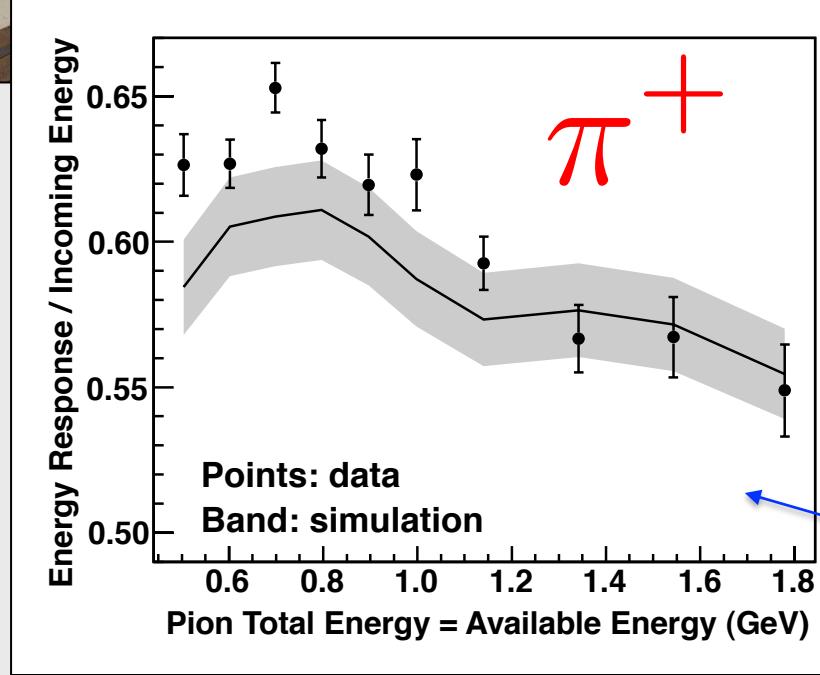


1 – 10 MeV mip hits

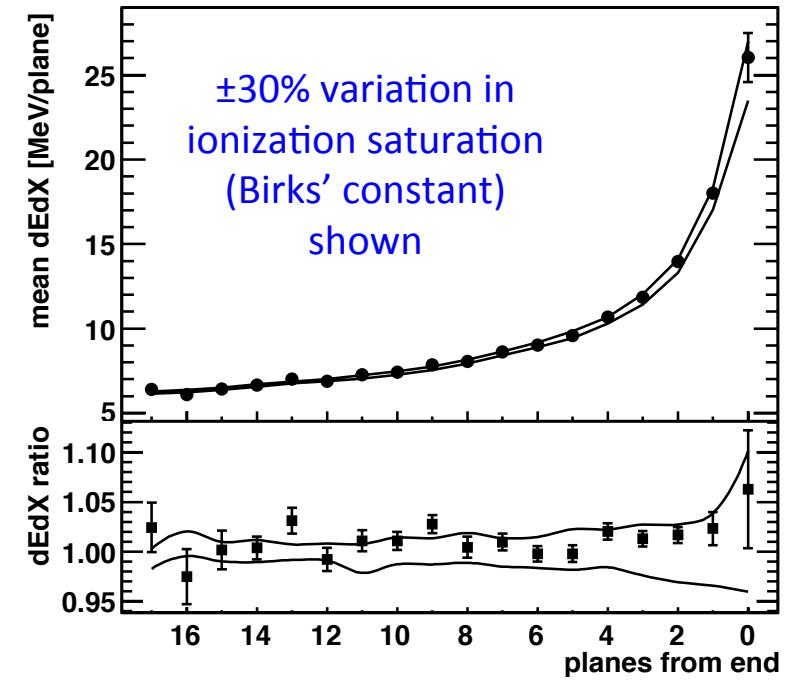
3. Recoil Energy Scale

Thank you everyone at MTest

Facility!!

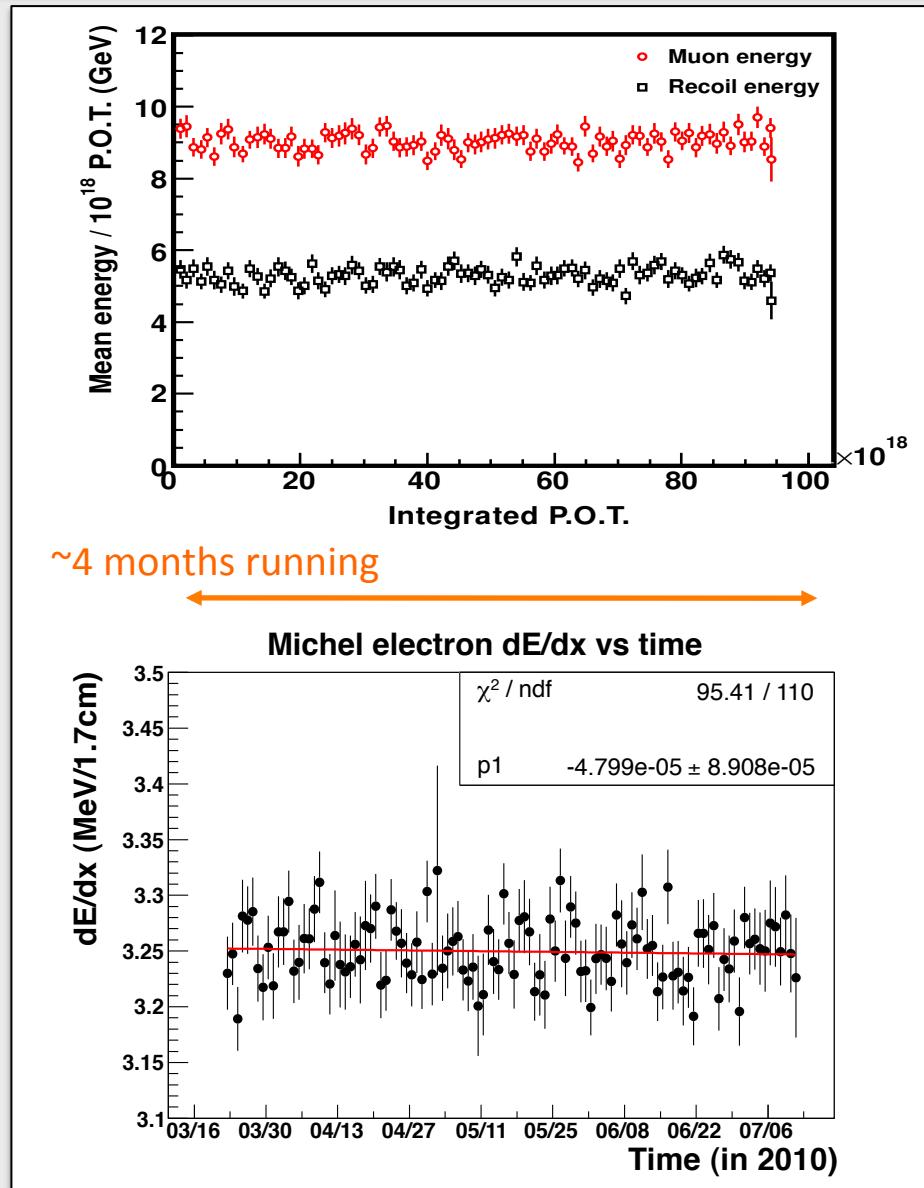


protons



high-energy charged pion response uncertainty $\approx 5\%$

3. Recoil Energy Scale



Muons

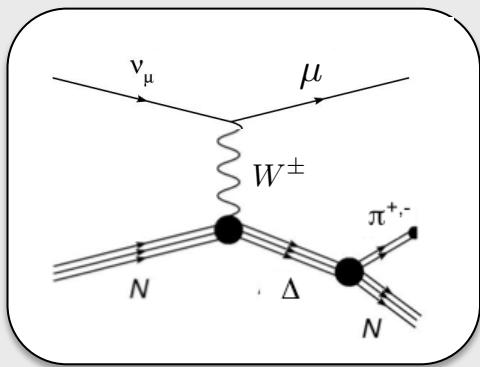
Recoil

Calibrated detector
very stable
at high and low
energy scales

Electron
 dE/dx

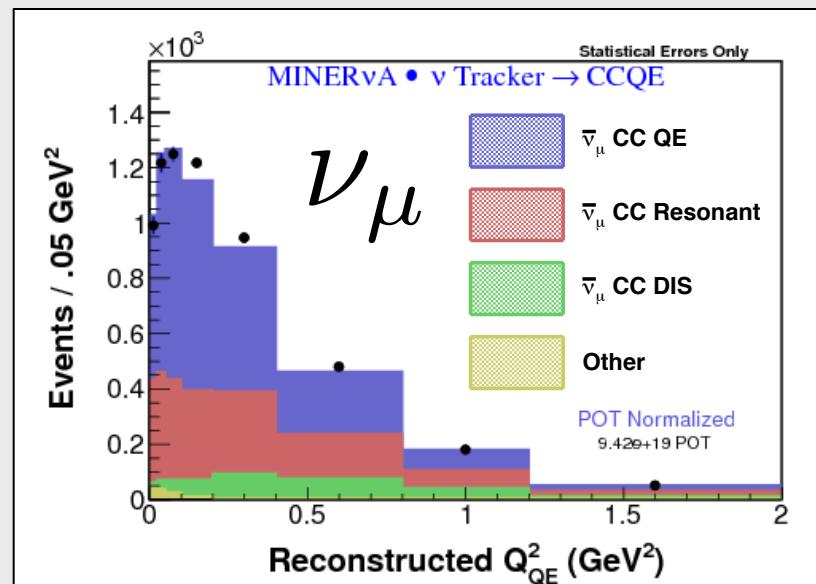
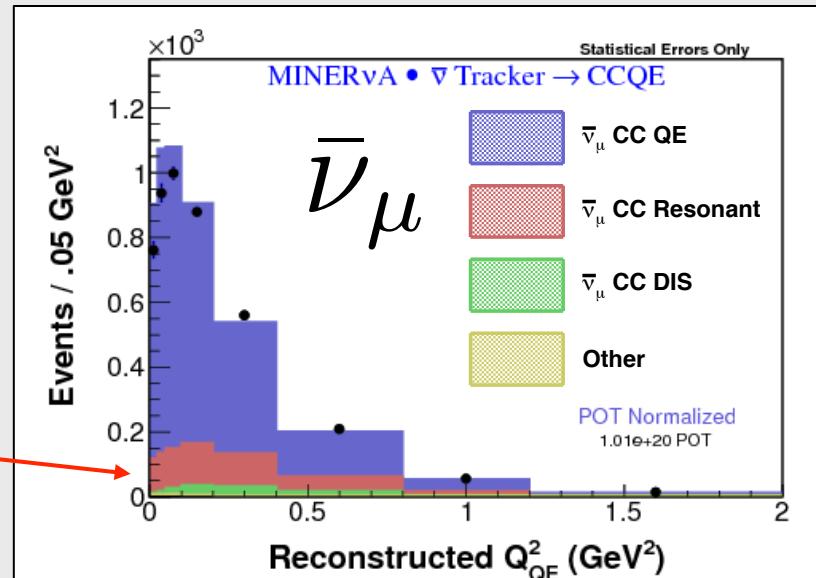
4. Primary Interaction Model

GENIE
2.6.2



- Main background from resonance production and decay to charged pions
 - Pion not tagged by recoil energy cut, OR
 - Pion absorbed in nucleus
- Rate constrained with data

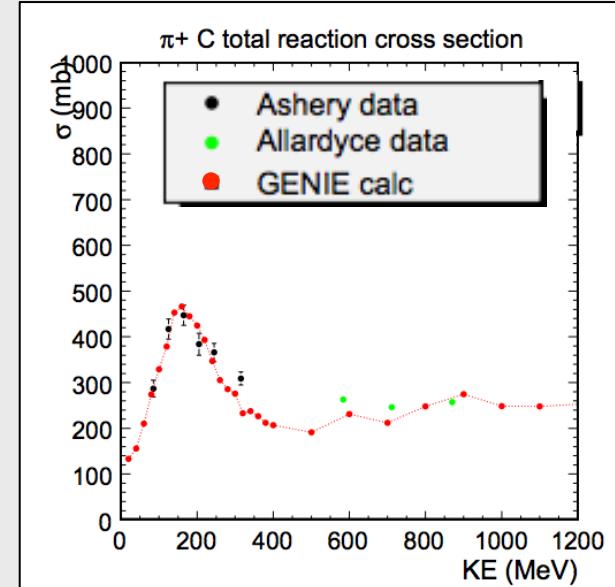
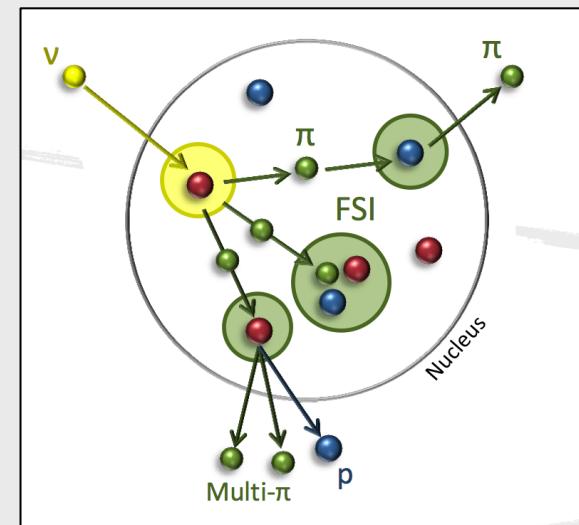
Model parameter	uncertainty
CC resonance prod. normalization	$\pm 20\%$
Resonance model parameter (M_A)	$\pm 20\%$
Non-resonance pion production	$\pm 50\%$



5. Final State Interactions

- Another way the nuclear environment really complicates things
 - Final state different from interaction vertex
- Important part of neutrino event generators
 - Tune with external hadron data
 - Data comparisons inform systematics
- Crucial piece of any analysis

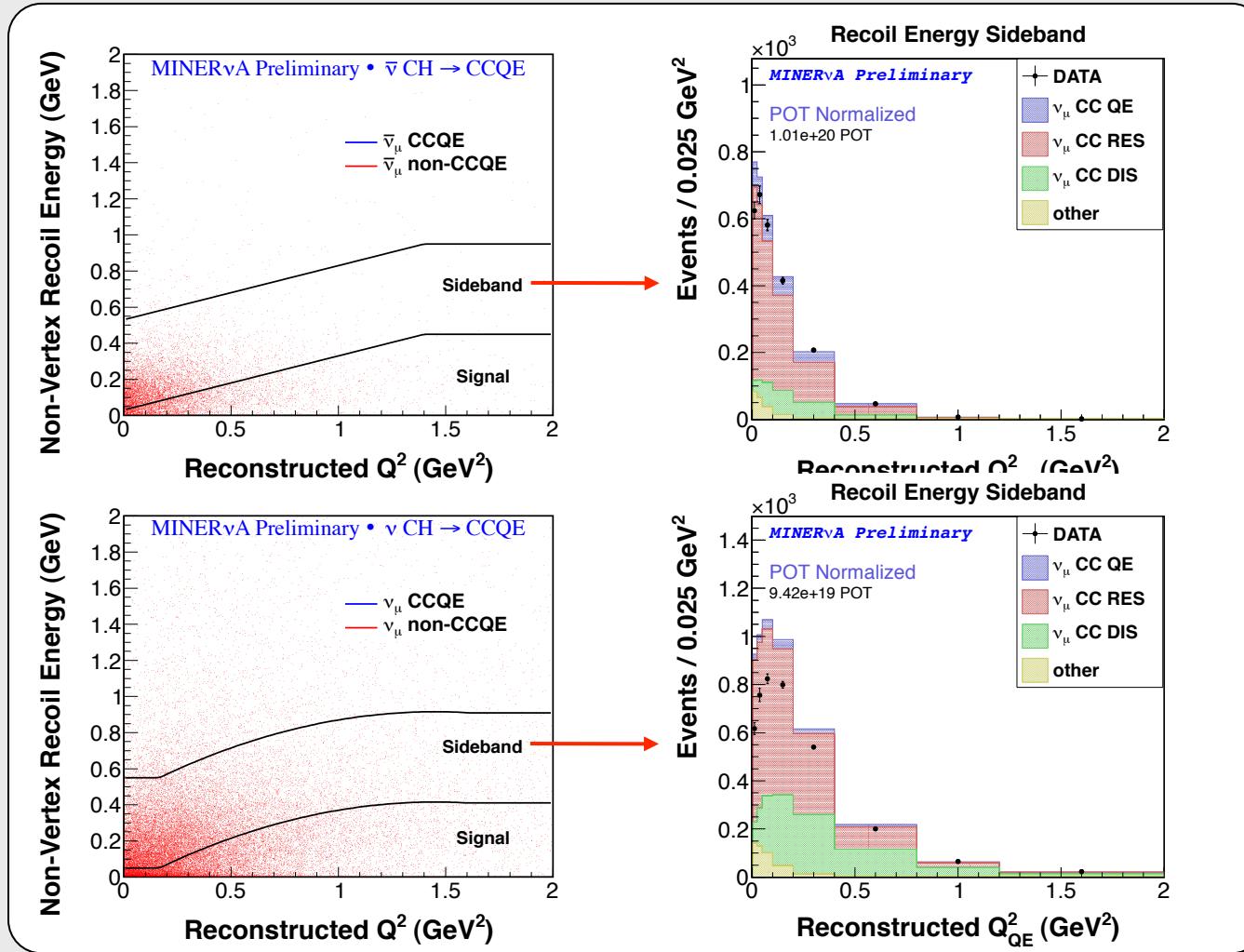
Model parameter	uncertainty
pion/nucleon mean path	$\pm 20\%$
pion/nucleon charge exchange	$\pm 50\%$
pion absorbtion	$\pm 30\%$
pion/nucleon inelastic cross-section	$\pm 40\%$
elastic cross sections	$\pm 10-30\%$



GENIE Physics Manual

Constraining Non-QE Backgrounds

- Given the challenge and large uncertainties on cross-section models and especially FSI, *constraining backgrounds with data* is very valuable



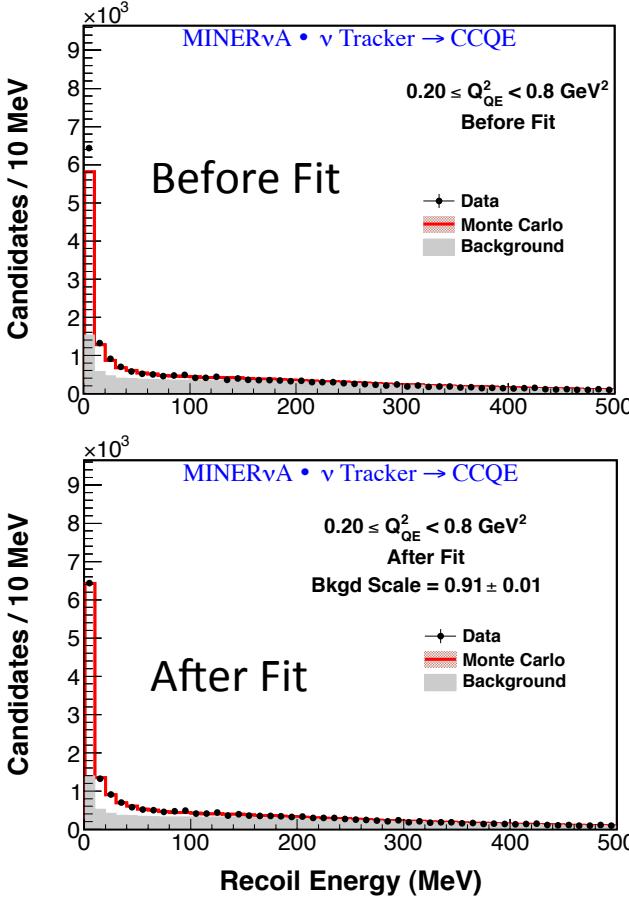
$\bar{\nu}_\mu$

ν_μ

Constraining Non-QE Backgrounds

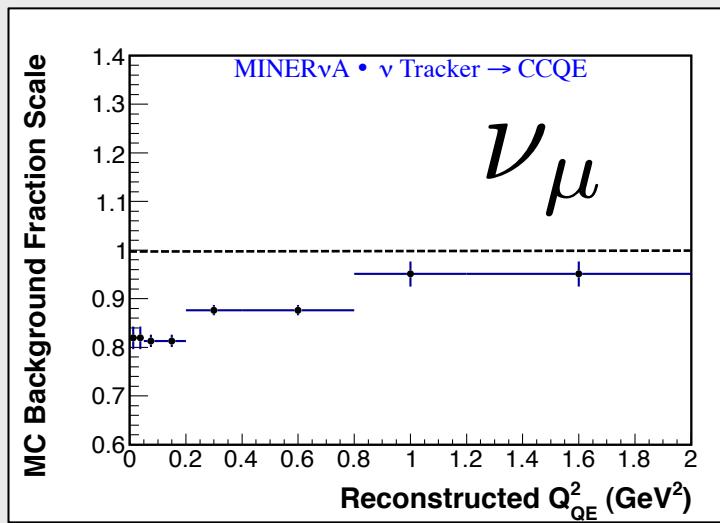
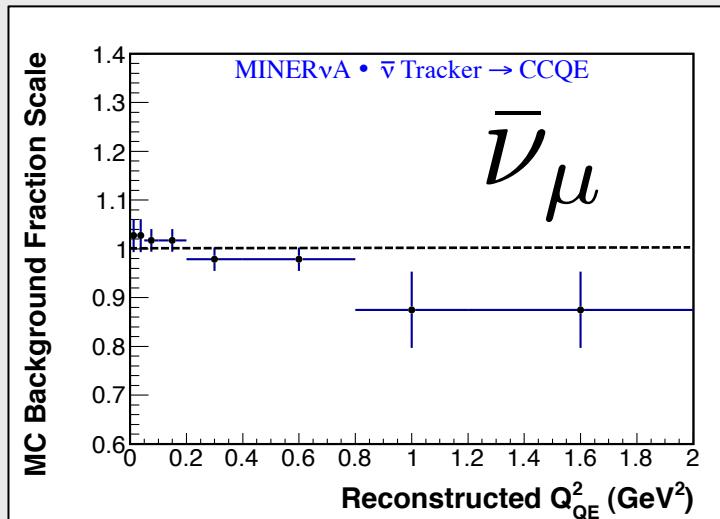
- Perform a fit in bins of Q^2_{QE} to set the relative signal – background fraction

One Sample Q^2_{QE} Bin



All Bins

Modify the predicted non-QE background rate by 5–15%

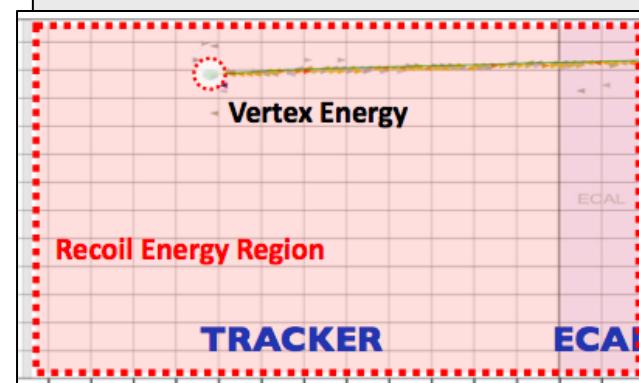
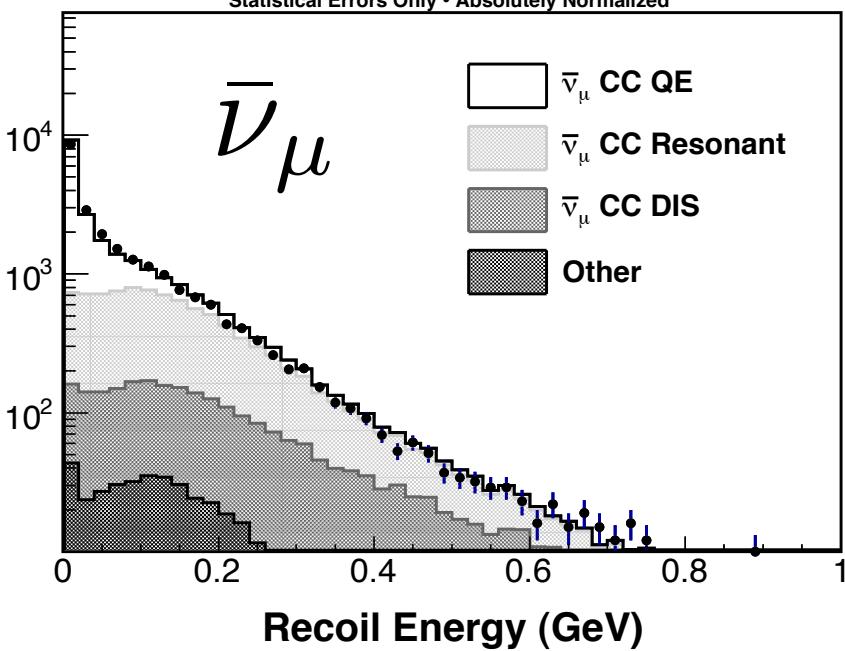


Final Recoil Distributions

$$0 < Q_{QE}^2 < 2.0 \text{ (GeV/c)}^2$$

Statistical Errors Only • Absolutely Normalized

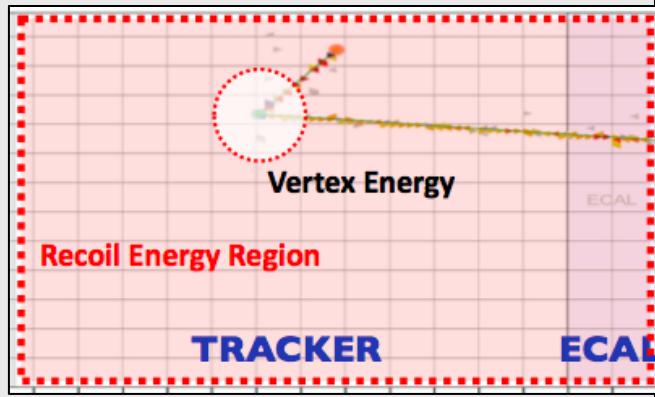
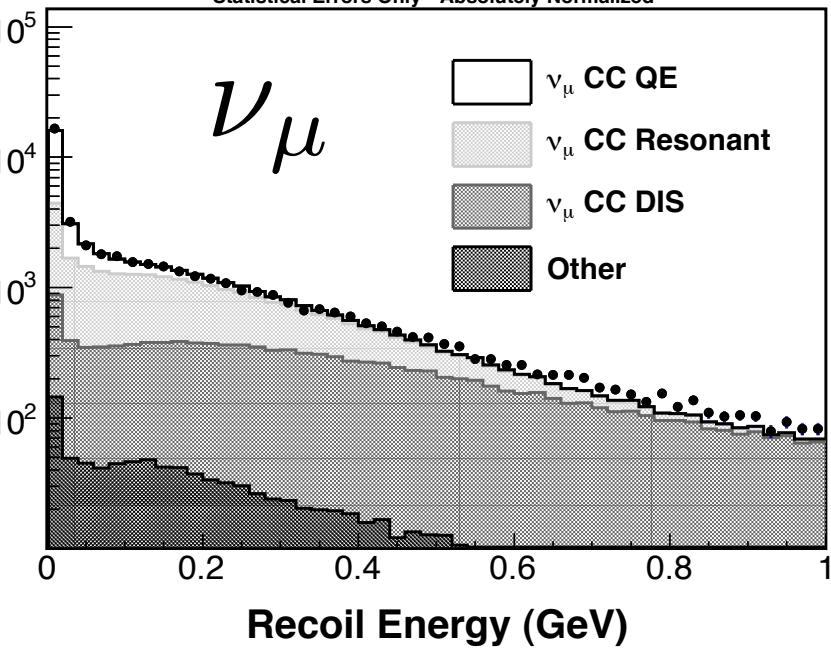
Events / 20 MeV



$$0 < Q_{QE}^2 < 2.0 \text{ (GeV/c)}^2$$

Statistical Errors Only • Absolutely Normalized

Events / 20



Differential Cross-section

Differential cross-section vs. **4-momentum transfer squared**

not to "generator Q^2 "

$$Q_{QE}^2 \rightarrow Q_{QE}^2$$

reco μ true μ
kinematics kinematics

backgrounds constrained by data

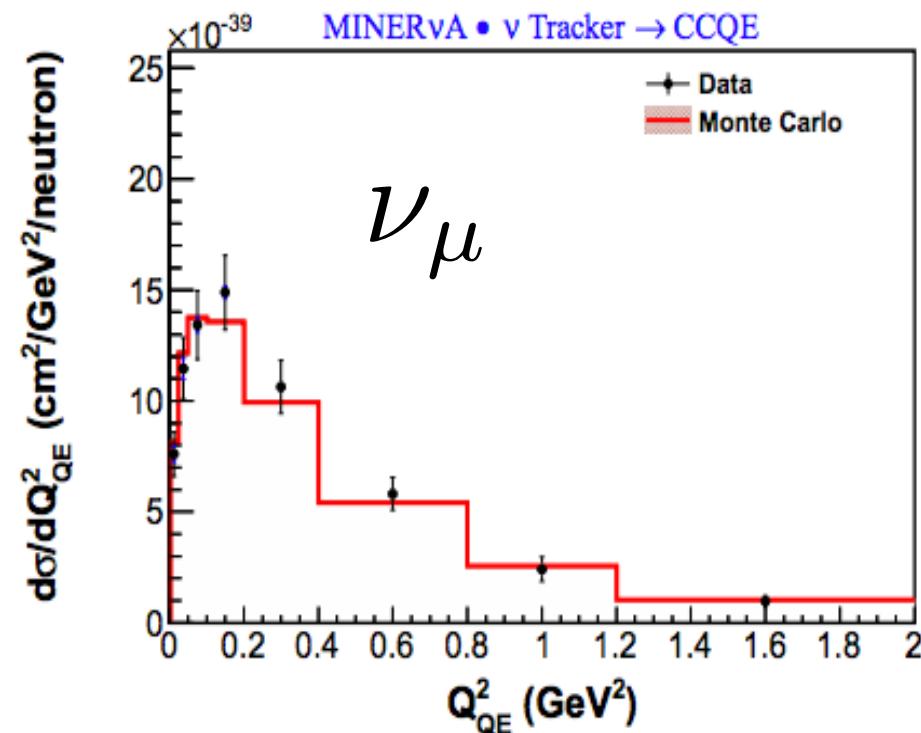
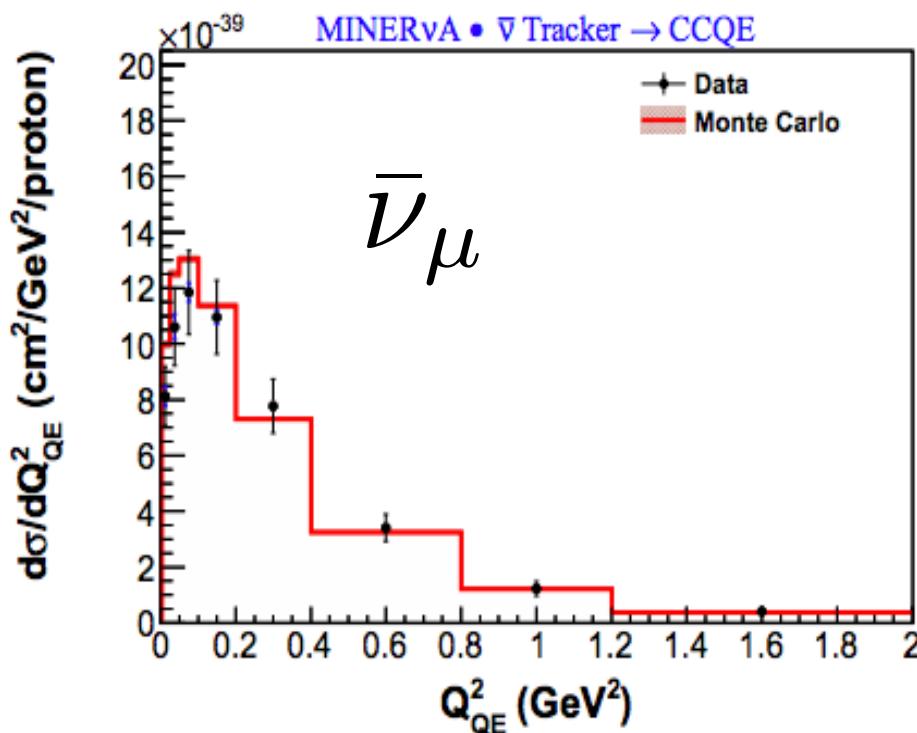
$$\left(\frac{d\sigma}{dQ_{QE}^2} \right)_i = \frac{1}{\Phi T} \frac{1}{\Delta Q_{QE}^2} \frac{\sum_j U_{ij} (N_{data,j} - N_{bg,j})}{\varepsilon_i}$$

flux, targets

bin size

muon eff constrained with data;
recoil eff uses MC away from vertex

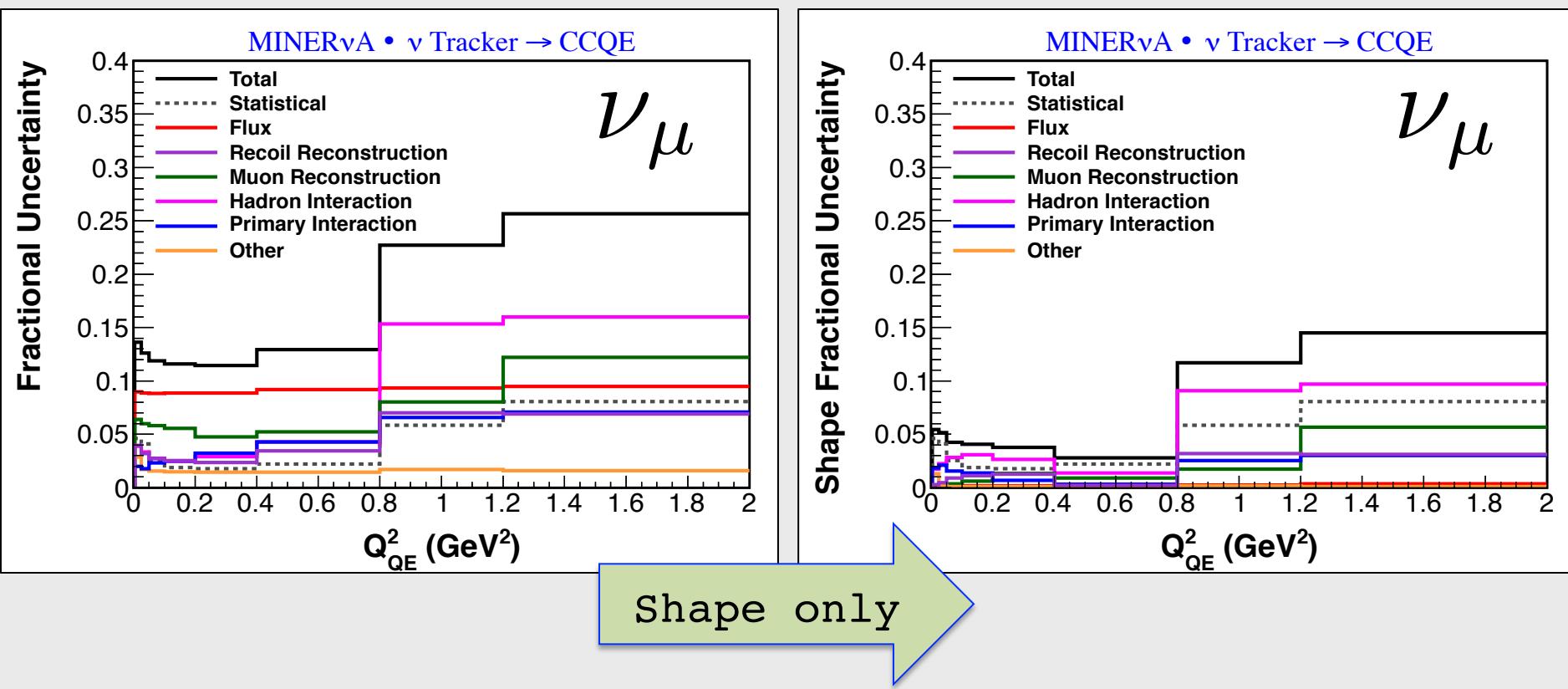
Differential Cross-Section Results



- To interpret these results, we will focus on two aspects:
 - The shape of the $d\sigma/dQ^2$ cross-section
 - The amount of energy very near the vertex

Interpretation #1: $d\sigma/dQ^2$ Shape

- Restricting to the *shape* of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



Interpretation #1: $d\sigma/dQ^2$ Shape

- The produced muon kinematics in an event are different if the (anti)neutrino scatters off an *independent quasi-free nucleon* (as assumed in most models) vs. scatters off *multiple nucleons in a correlated state*.
- We do not, therefore, want to use a model to “correct” the Q^2_{QE} inferred from observed muon kinematics to the “true” Q^2 generated in that model.
- Instead, we are careful to *only correct for detector smearing effects* and how they impact the calculated Q^2 distribution
 - E_μ and θ_μ smearing only

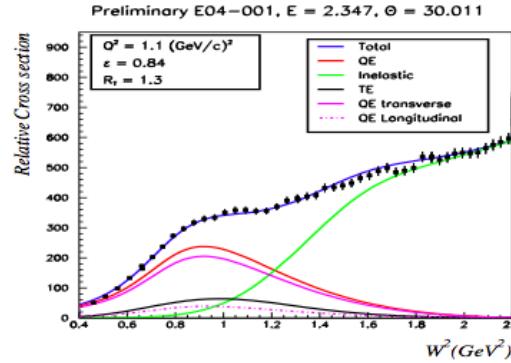
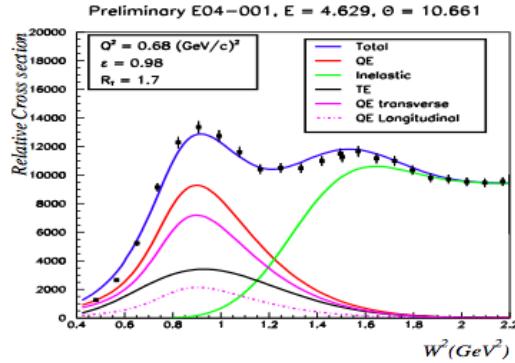
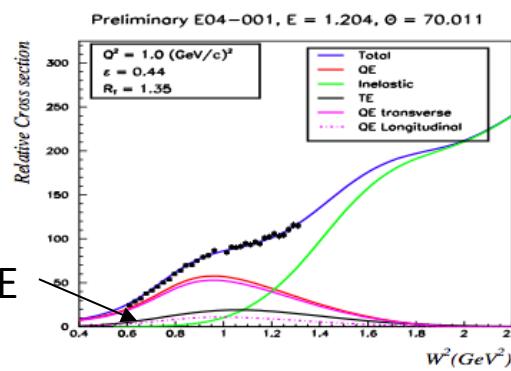
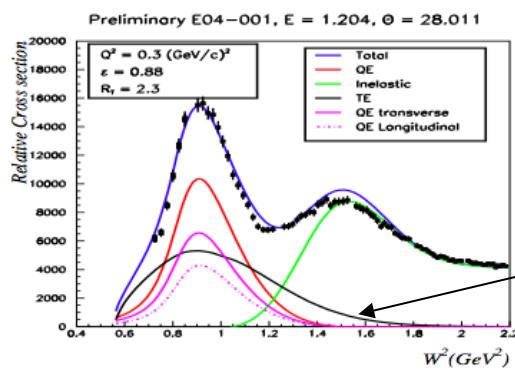
$$E_\nu^{QE} = \frac{2(M_n - E_B) E_\mu - [(M_n - E_B)^2 + m_\mu^2 - M_p^2]}{2[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$

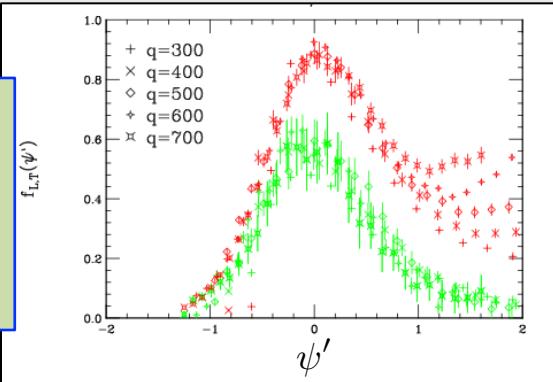
Interpretation #1: $d\sigma/dQ^2$ Shape

- Models that introduce nuclear correlations of various kinds *tend to modify the QE cross-section as a function of Q^2* (for a given ν energy spectrum)
- The models:
 - Relativistic Fermi Gas (RFG), $M_A = 0.99 \text{ GeV}/c^2$
 - The canonical model in modern event generators used by all neutrino experiments
 - Relativistic Fermi Gas (RFG), $M_A = 1.35 \text{ GeV}/c^2$
 - Motivated by recent measurements where this change was fairly successful at reproducing data
 - Nuclear Spectral Function (SF), $M_A = 0.99 \text{ GeV}/c^2$
 - More realistic model of the nucleon momentum – energy relationship than standard RFG
 - Transverse Enhancement Model (TEM), $M_A = 0.99 \text{ GeV}/c^2$
 - Empirical model which modifies the magnetic form factors of bound nucleons to reproduce an enhancement in the transverse cross-section observed in *electron-nucleus scattering* attributed to the presence of meson exchange currents (MEC) in the nucleus

Transverse Enhancement Model



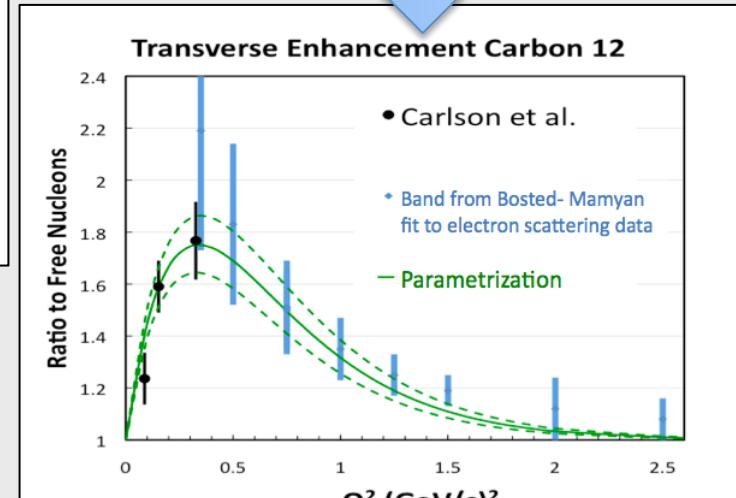
An attempt to parameterize this feature we saw in electron scattering



J. Carlson, et al., PRC 65, 024002 (2002)

Fits in Q^2 bins

$$R_T = \frac{QE_{transverse} + TE}{QE_{transverse}}$$

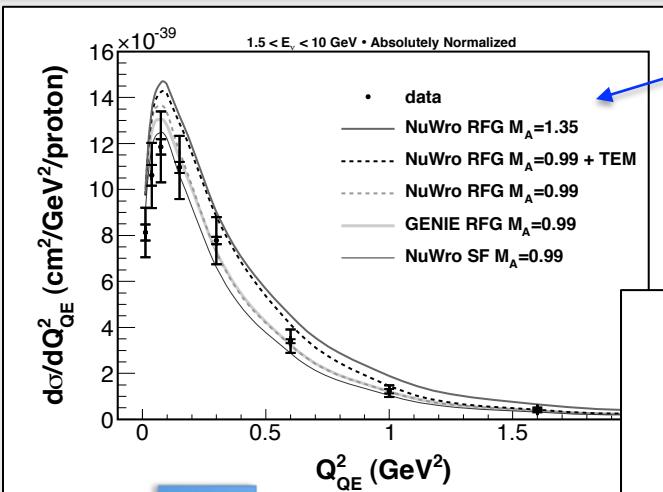


$$G_M^p(Q^2)$$

$$G_M^n(Q^2)$$

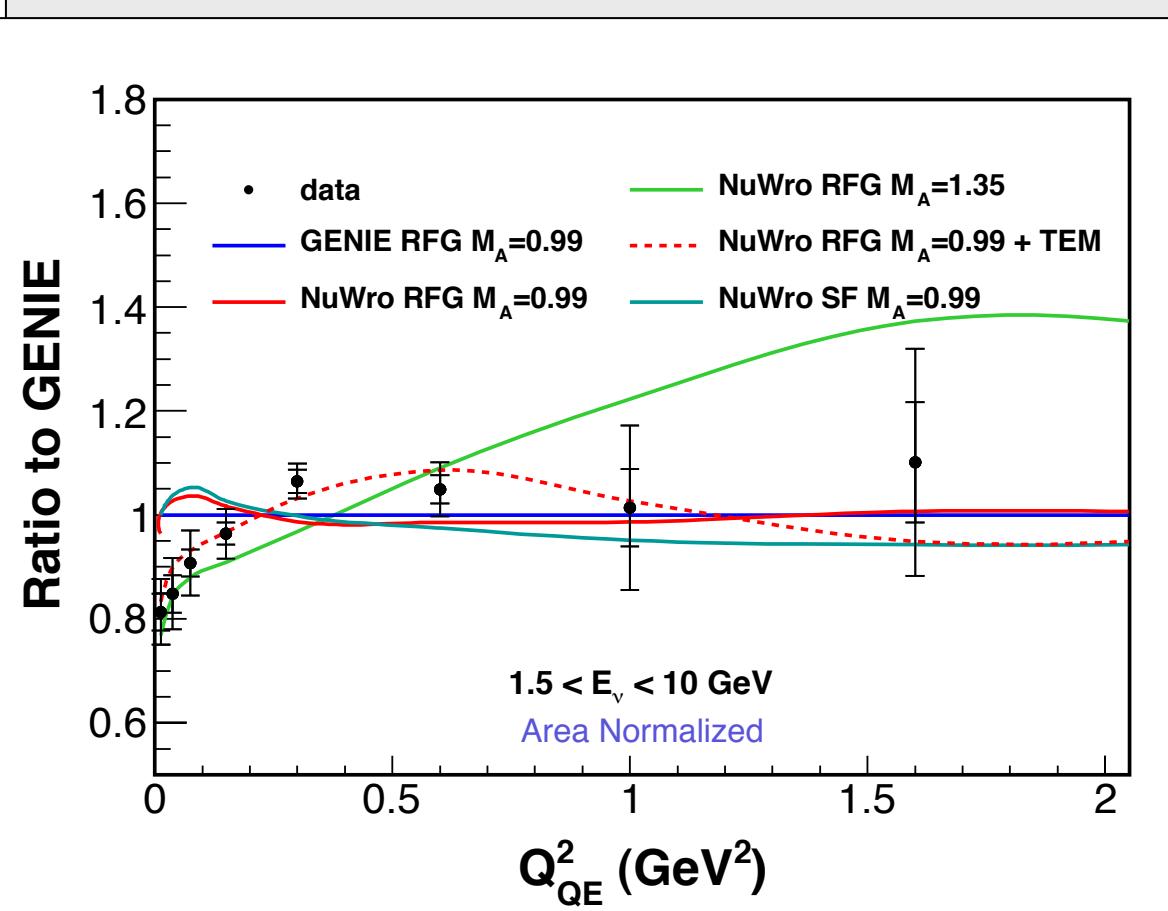
Applied as modifications of the **magnetic form factors for bound nucleons**

$d\sigma/dQ^2$ Shape - Antineutrino



$\bar{\nu}_\mu$

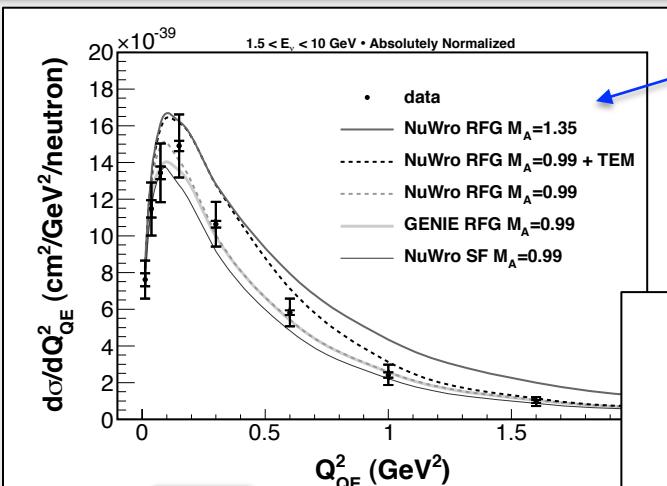
emphasize shape



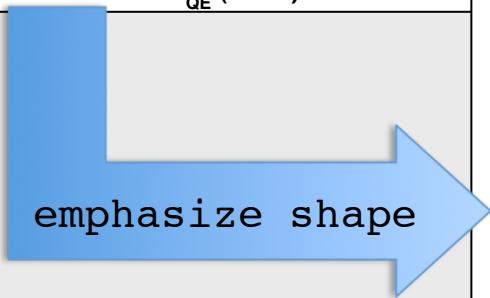
Normalize each prediction and data to GENIE prediction and form ratio

$d\sigma/dQ^2$ Shape - Neutrino

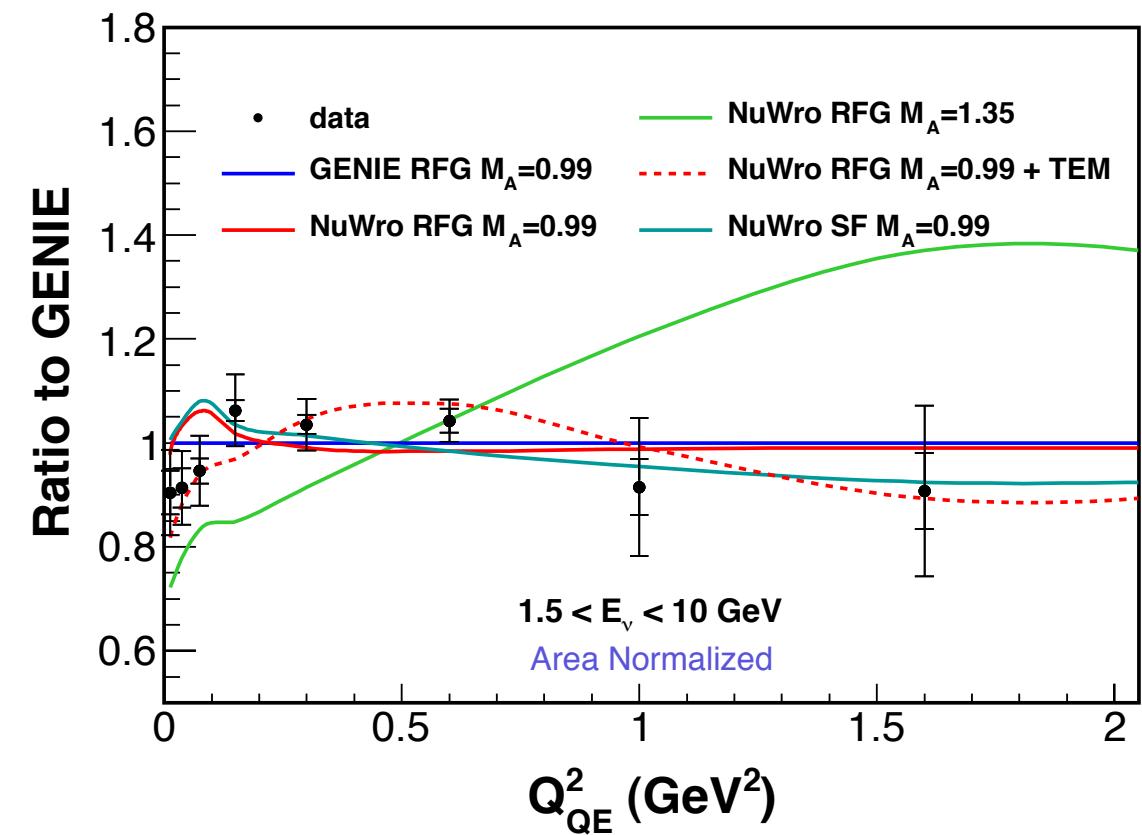
ν_μ



Absolute cross-section



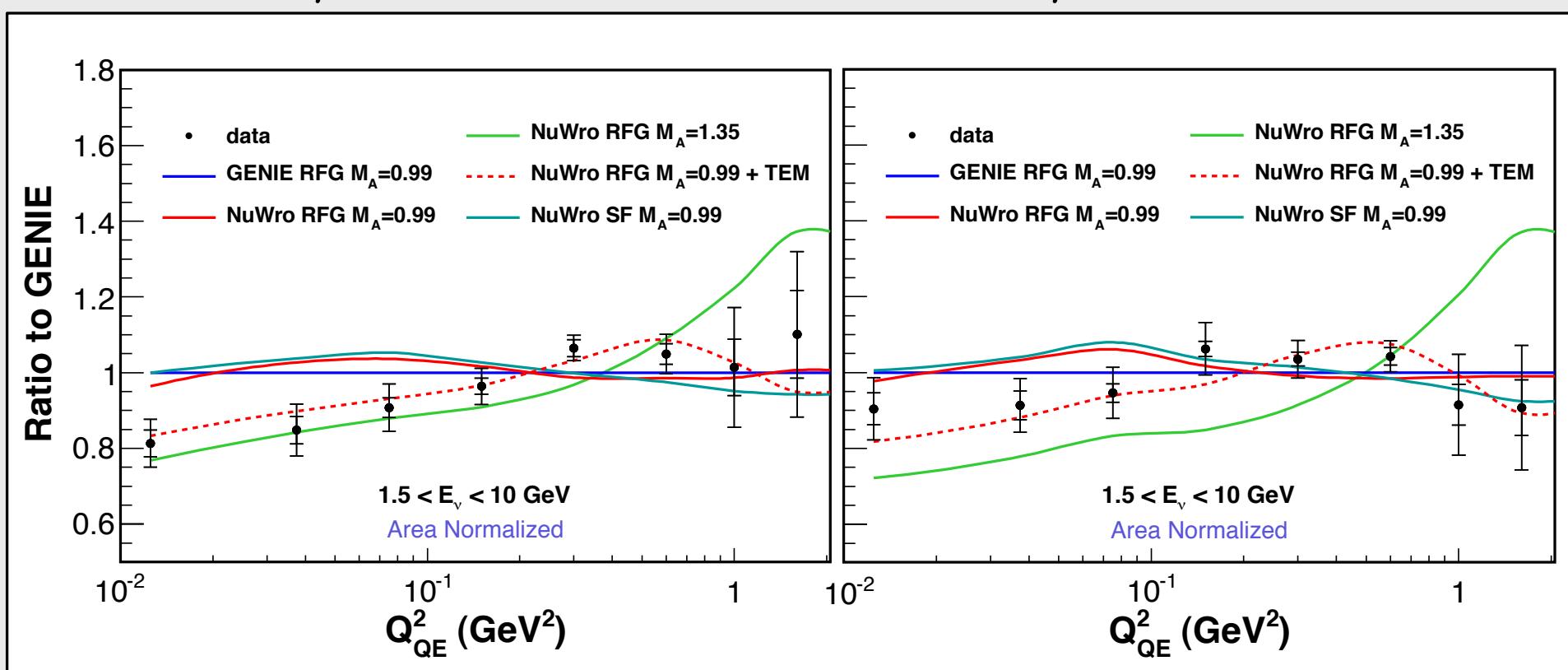
Normalize each prediction and data to GENIE prediction and form ratio



$d\sigma/dQ^2$ Shape

$\bar{\nu}_\mu$ CCQE

ν_μ CCQE



same plots with log x-axis to see low Q^2 region

Interpretation #1: $d\sigma/dQ^2$ Shape

- The shape of the measured neutrino and antineutrino $d\sigma/dQ^2$ cross-sections *disfavor a standard relativistic Fermi gas* implementation for carbon with $M_A = 0.99 \text{ GeV}/c^2$

$\bar{\nu}_\mu$

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate $\chi^2/\text{d.o.f.}$	2.64	1.06	2.90	2.14
Shape $\chi^2/\text{d.o.f.}$	2.90	0.66	1.73	2.99

ν_μ

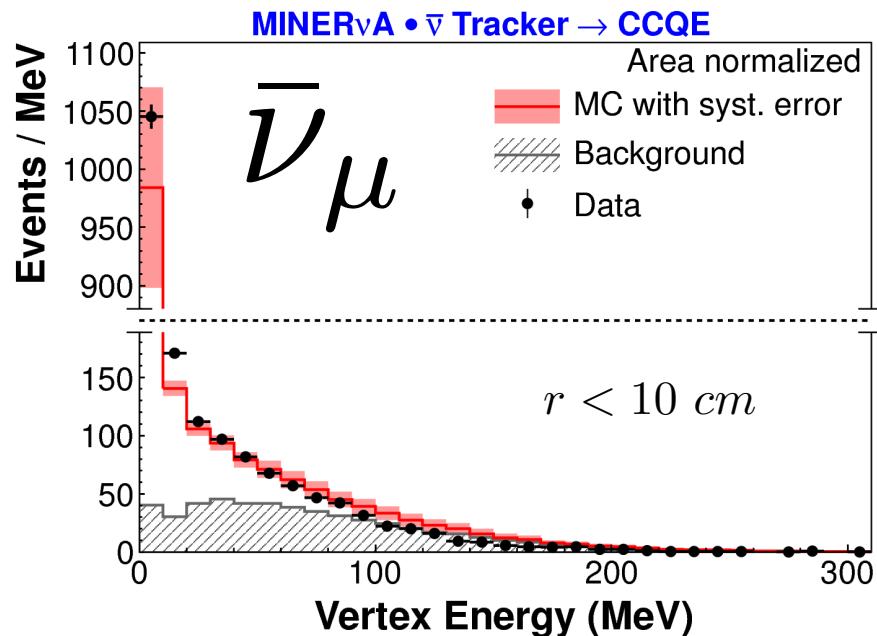
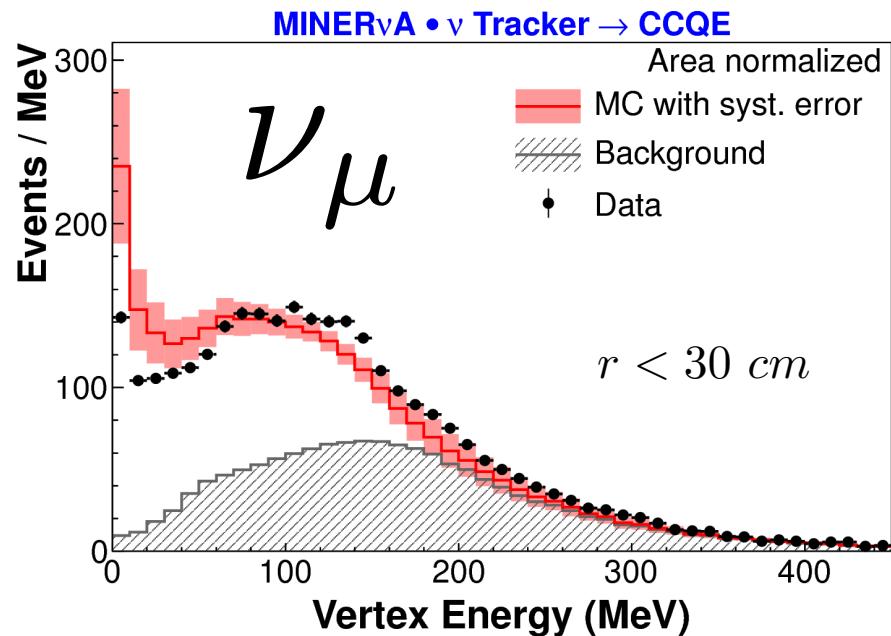
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c ²)	0.99	0.99	1.35	0.99
Rate $\chi^2/\text{d.o.f.}$	3.5	2.4	3.7	2.8
Shape $\chi^2/\text{d.o.f.}$	4.1	1.7	2.1	3.8

- Changing only the axial-mass $M_A = 1.35 \text{ GeV}/c^2$ does marginally improve agreement with data
- The data most prefer an empirical model that attempts to transfer the observed *enhancement* in electron-nucleus scattering *attributed to meson exchange current (MEC) contributions* to neutrino-nucleus scattering

Interpretation #2: Vertex Energy

- Microscopic models of multi-nucleon (np-nh) contributions are not presently available in event generators at NuMI energies
- No prediction for the hadron kinematics in these classes of events
- In general, *multi-nucleon emission is expected in interactions with correlated nucleons*, so this provides another possible signature
 - Additional nucleons beyond the expected neutron (antineutrino) or proton (neutrino)
- So, we *look very near the interaction vertex* in neutrino and antineutrino events for *excess energy* coming from charged nucleons (protons)
 - Recall, we purposefully avoided this region when selecting QE candidates
 - Because we did not want our QE event selection biased by the MC not having these multi-nucleon events; now we look in the ignored region
 - Final State Interaction (FSI) uncertainties are very important in this analysis

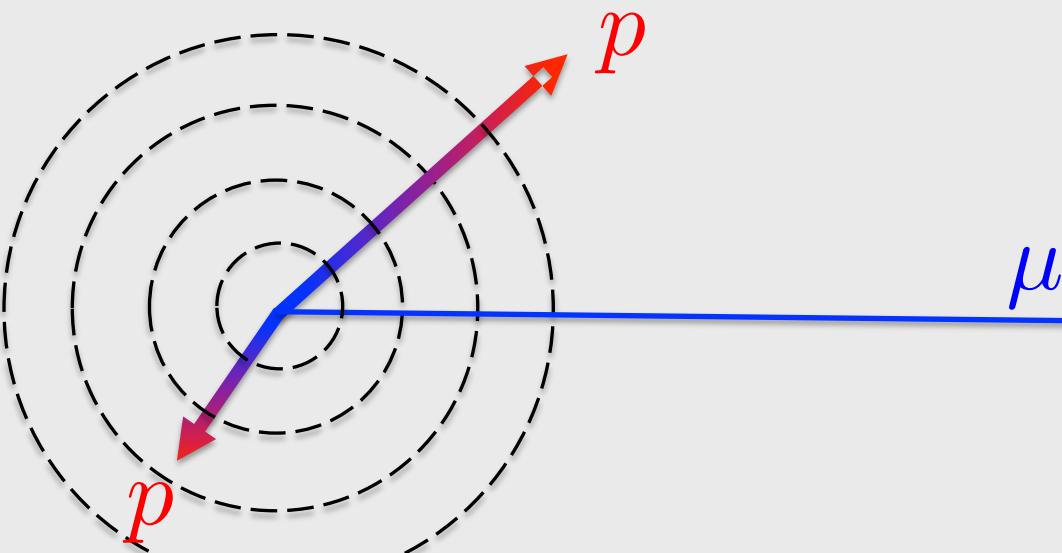
Vertex Energy



- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- At this point, we make the *working assumption* that the additional vertex energy per event in data is *due to protons*

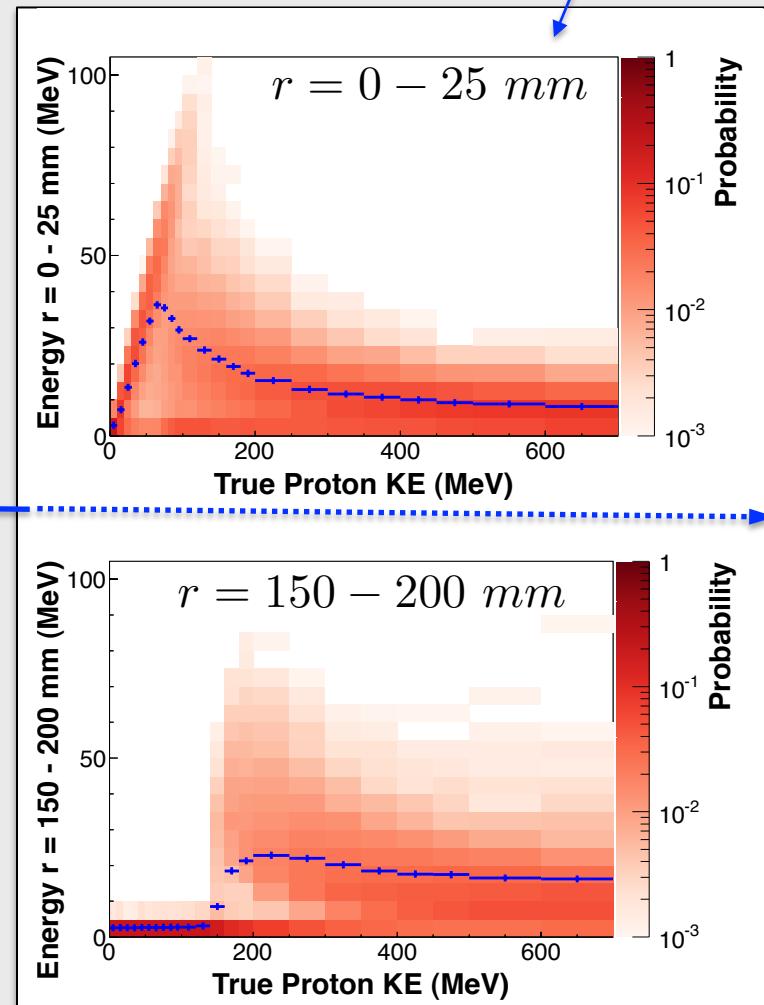
Vertex Energy

- Examine annular rings around the reconstructed vertex
 - Out to 10 cm for antineutrino (~ 120 MeV proton)
 - Out to 30 cm for neutrino (~ 225 MeV proton)

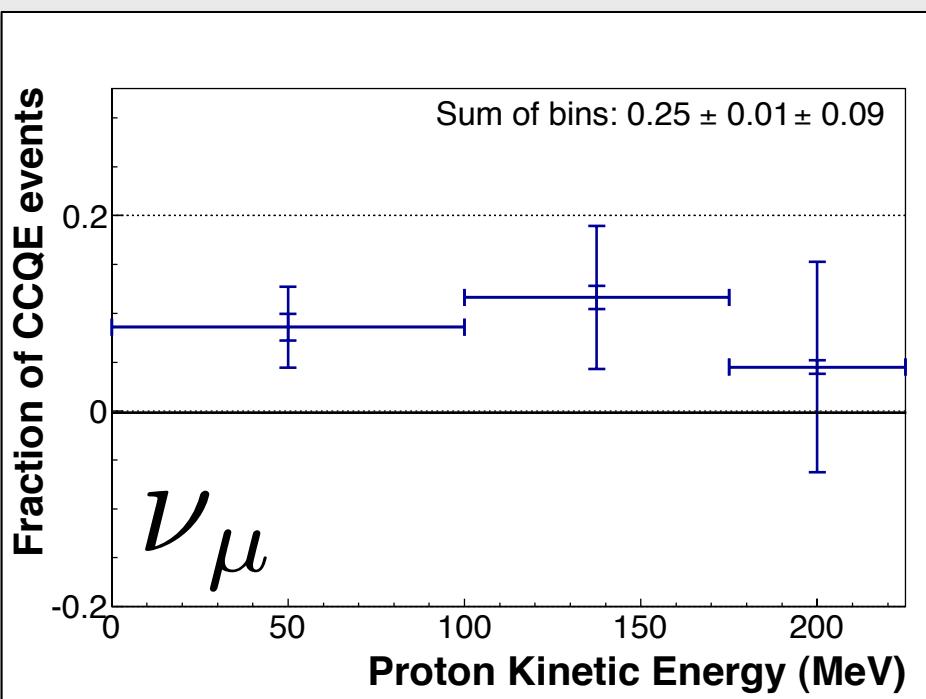


Note: to add visible energy to an inner annulus you must **add a charged hadron**, not just increase energy of an existing one

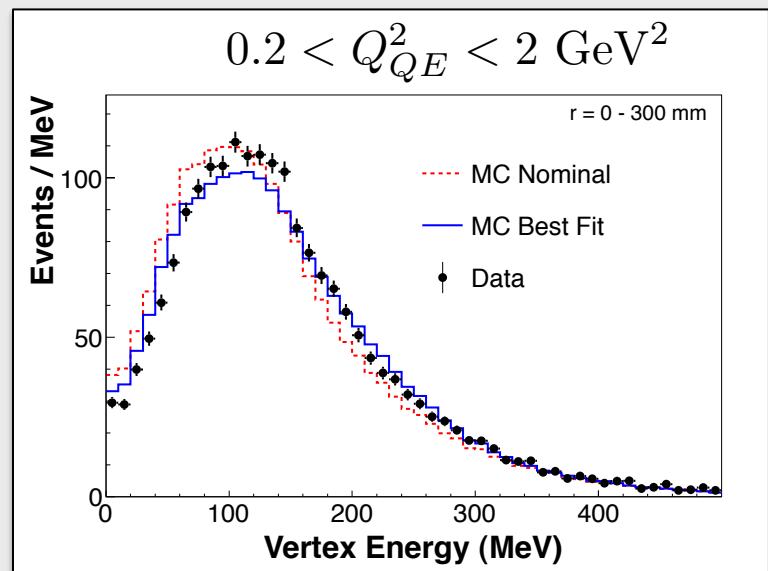
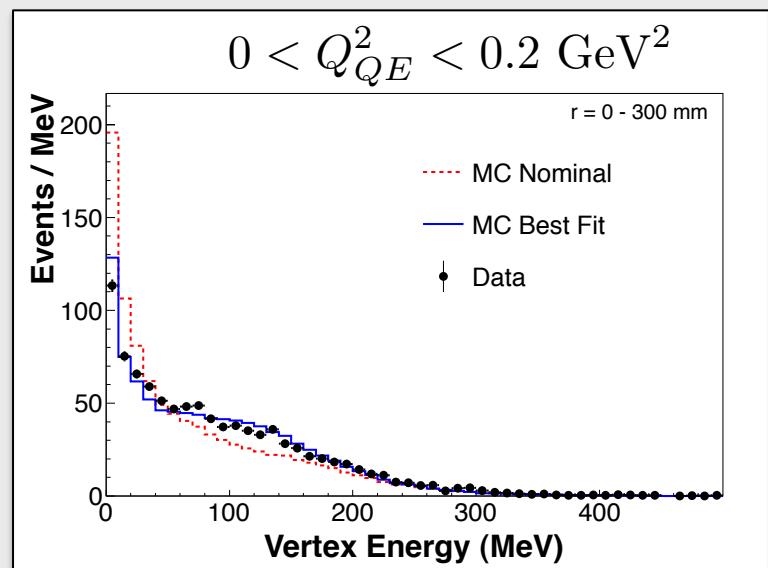
E_{vis} in that annulus vs. true $\text{KE}_{\text{proton}}$



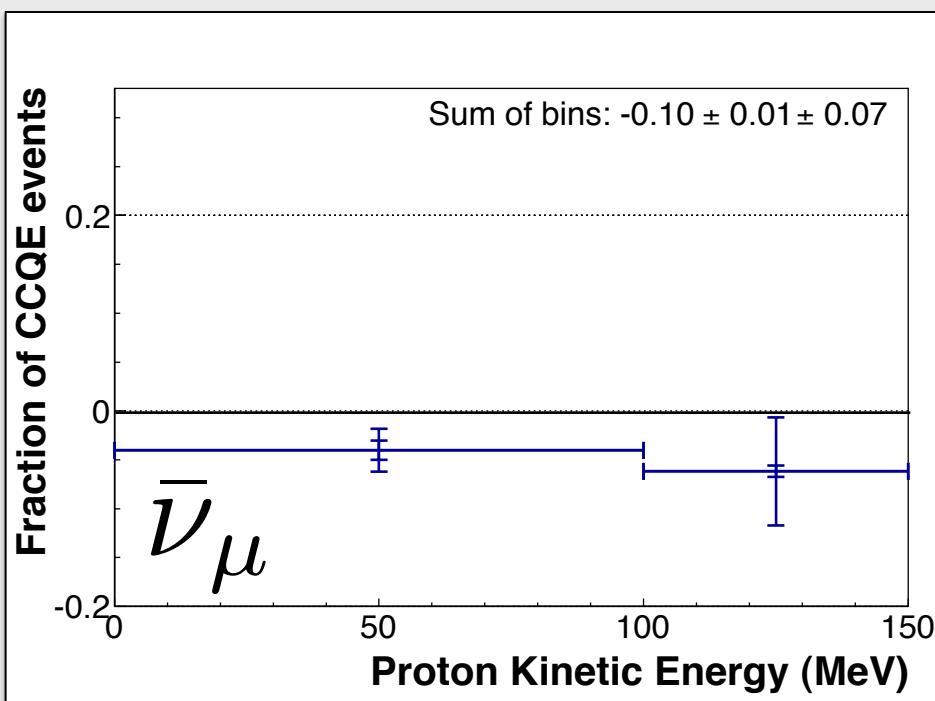
Vertex Energy - Neutrinos



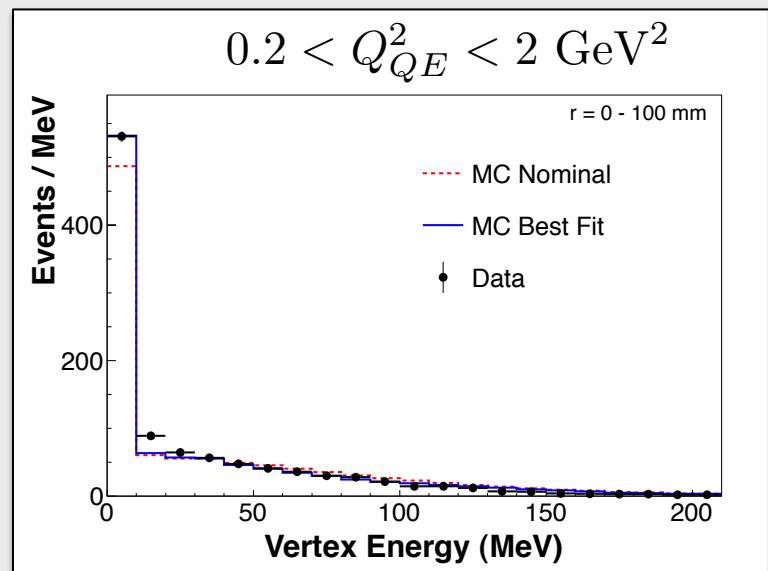
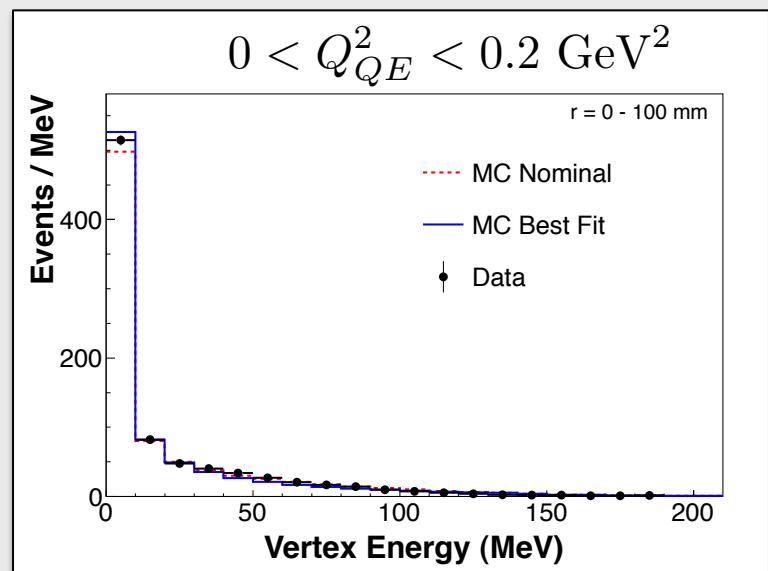
We find that adding an additional low-energy proton ($KE < 225$ MeV) to **(25 ± 9)% of QE events** improves agreements with data



Vertex Energy - Antineutrinos

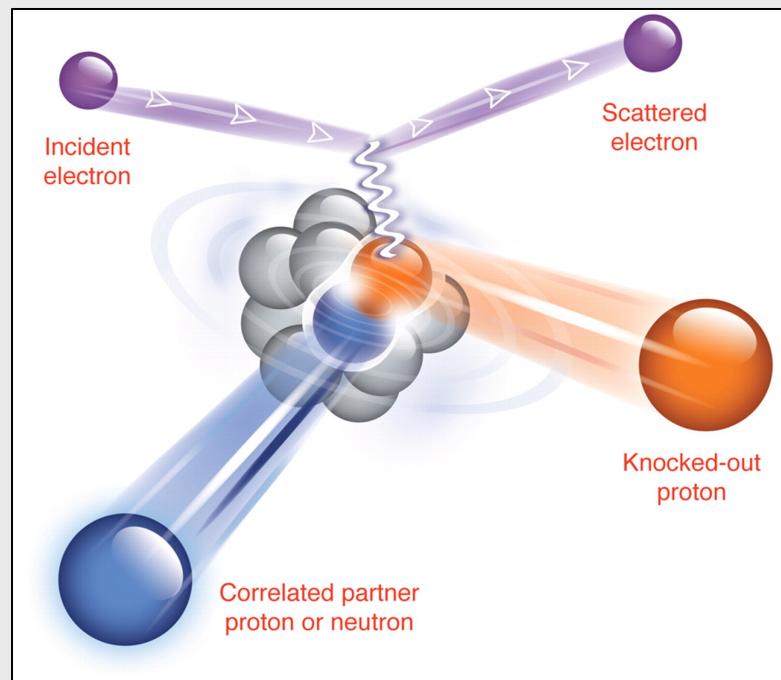


No such addition required
for antineutrinos. Slight
reduction if anything.
(-10 ± 7)% of QE events

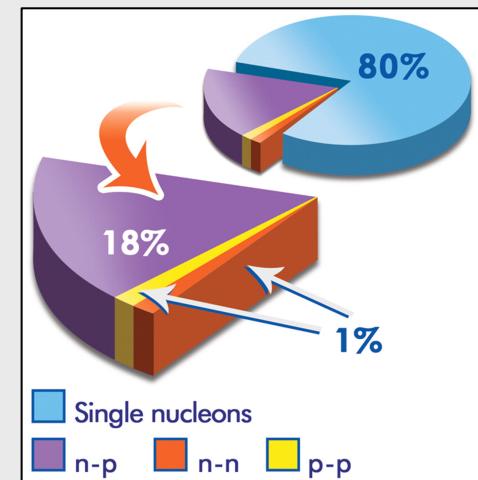


Interpretation #2: Vertex Energy

- What do multi-nucleon models predict?
 - For short-range correlations, electron-scattering measurements on ^{12}C indicate a predominance of np pairs in the initial state
 - Implies final states of nn in antineutrino and pp in neutrino CC scattering
 - For other forms of correlation, depends on model
- FSI a challenge in this analysis, but
 - All systematics considered as in $d\sigma/dQ^2$ analysis
 - Neutrino / antineutrino correlation = +0.7
 - Hard to explain opposite trend with any of our systematics



R. Subedi et al.,
Science 320, 1476
(2008)



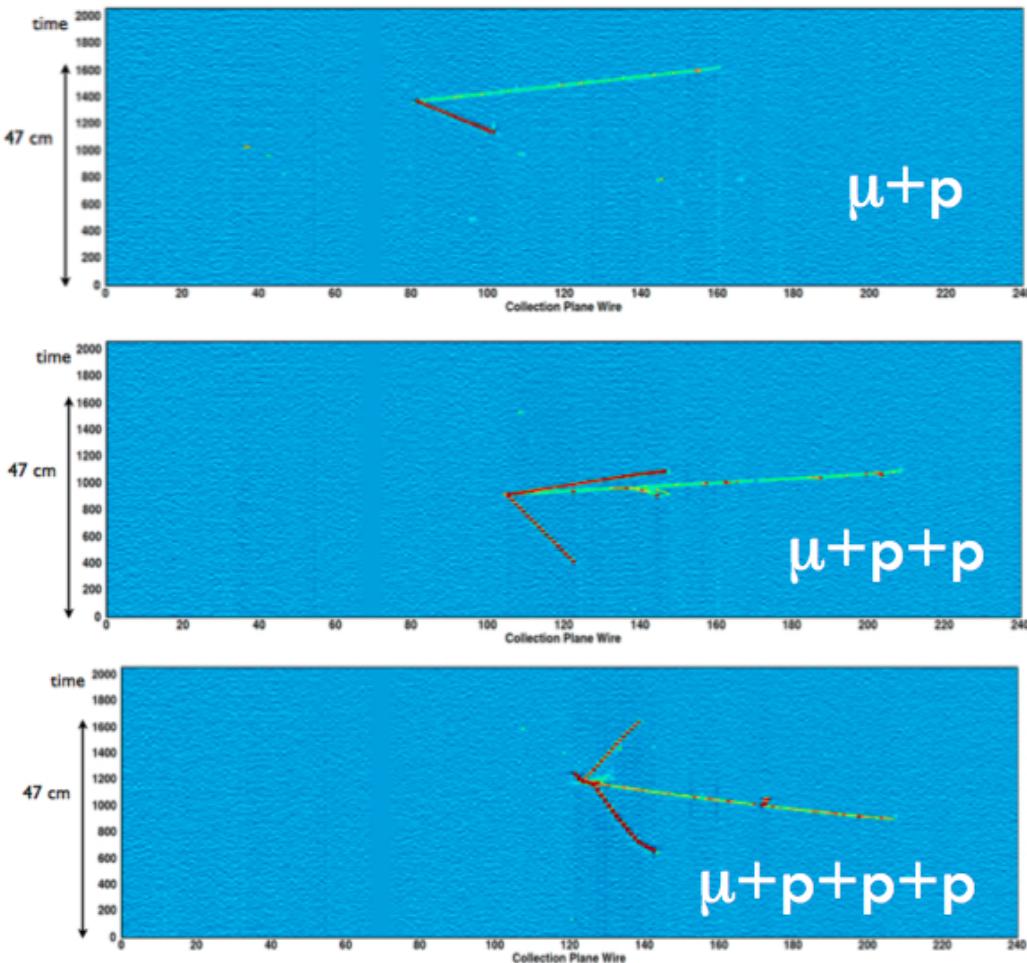
Summary of Results

- MINERvA has measured the differential cross-section $d\sigma/dQ^2$ for neutrinos and antineutrinos on a hydrocarbon (CH) target
 - Integrated over the NuMI fluxes between 1.5 – 10 GeV
 - The shape of both of these cross-sections disfavor a simple RFG modeling of the carbon nucleus for scattering at these energies, strengthening the call for improved modeling in (anti)neutrino scattering
 - The data most prefer a model derived from an observed enhancement of the transverse part of the cross-section in electron scattering attributed to meson exchange currents, a form of long-range multi-nucleon correlation
- MINERvA has investigated the energy very near the vertex in CCQE rich samples for both neutrinos and antineutrinos
 - The GENIE Monte Carlo under-predicts the amount of low-energy hadronic particle content in the neutrino sample
 - A model-dependent fit (assume protons) indicates that an additional sub-200 MeV proton in $(25 \pm 9) \%$ of QE events is consistent with the data

Future Directions In CCQE @ MINERvA

- Further quantify *correlations between neutrino and antineutrino* systematics
- *Michel electron tag* in neutrino sample $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
- *Neutron tagging* in antineutrino sample
- $\mu + p$ reconstruction. Push on *low-energy tracking* threshold of protons to reconstruct final states like $\mu + p + p$
- *Double-differential* cross sections in muon kinematics
$$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$$
- QE cross section vs. energy, $\sigma_{QE}(E)$
- Extend to *lower muon energies* by not requiring MINOS reconstruction
- QE scattering on other *nuclear targets* (Fe, Pb) in MINERvA
- *QE-like* final state cross sections

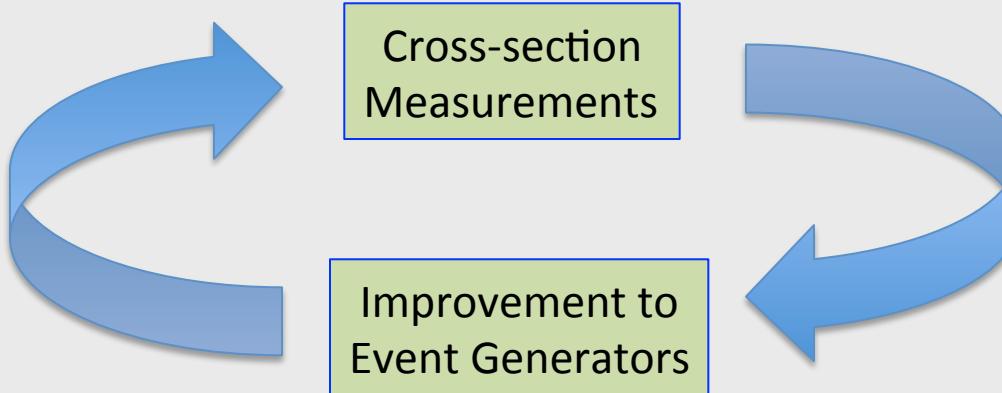
Future Directions In CCQE



J. Spitz, arXiv:1009.2515 [hep-ex]

- LArTPCs a real advantage in reconstructing hadronic side of the interaction
- ArgoNeuT (NuMI energies)
- MicroBooNE (<1 GeV)

Some Closing Remarks



- These results are one example of new data in neutrino-nucleus scattering that can help us improve modeling of these processes
- A feedback loop is critical to get the most out of these data and to eventually come away with an improved generator for the future
- Many are aware; lots of buy-in from the community; upcoming workshops
 - [Neutrino-Nucleus Generators Workshop](#), University of Pittsburgh, June 9-11
 - [INT Workshop on Neutrino-Nucleus Scattering for Oscillation Exp](#), Dec 3-13

Some Closing Remarks

- MINERvA looks forward to being an integral part of this effort to improve neutrino interaction modeling for future neutrino experiments and providing lots of input to the process
 - >20 students working on Ph.Ds – partial list of measurements

- 1) "Differential Cross Sections vs Q2 in Muon Anti-Neutrino Quasi-Elastic Interactions"
- 2) "Differential Cross Sections vs Q2 in Muon Neutrino Quasi-Elastic Interactions"
- 3) "Differential Cross Sections vs Q2 in Electron Neutrino Quasi-Elastic Interactions"
- 4) "Activity near the interaction vertex in Neutrino and Anti-neutrino Quasi-Elastic Interaction vertices"
- 5) "Comparisons of Neutrino Quasi-Elastic scattering on carbon, lead, iron and scintillator"
- 6) "Absolute Cross Sections vs neutrino Energy, muon momentum and angle in Muon Anti-Neutrino Quasi-Elastic Interactions"
- 7) "Absolute Cross Sections vs neutrino Energy, muon momentum and angle in Muon Neutrino Quasi-Elastic Interactions"
- 8) "Measurement of the Total Neutrino Charged Current Cross Section on Scintillator"
- 9) "Measurement of the Total Anti-Neutrino Charged Current Cross Section on Scintillator"
- 10) "Ratios of Neutrino and Anti-Neutrino Total Charged Current Cross-sections on carbon, lead, iron and scintillator"
- 11) "Kinematics of Inclusive Charged Current Scattering by neutrinos on Scintillator from 2-8GeV"
- 12) "Kinematics of Inclusive Charged Current Scattering by anti-neutrinos on Scintillator from 2-8GeV"
- 13) "Charged Pion production in Neutrino Charged Current scattering"
- 14) "Charged Pion production in Anti-Neutrino Charged Current scattering"
- 15) "Neutral Pion production in Neutrino Charged Current scattering"
- 16) "Neutral Pion production in Anti-Neutrino Charged Current scattering"
- 17) "Coherent Charged Pion production by Muon Neutrinos at 2-20GeV"
- 18) "Coherent Neutral Pion production by Muon Neutrinos at 2-20GeV"
- 19) "Coherent Charged Pion production by Muon Anti-Neutrinos at 2-20GeV"
- 20) "Strange Particle Production in 2-10GeV neutrinos and anti-neutrinos"
- 21) "Nuclear Dependence of Coherent Charged Pion production from 2-10GeV"
- 22) "Absolute Neutrino Cross Sections on Helium vs Neutrino Energy"
- 23) "Ratios of Inclusive Neutrino and Anti-Neutrino Charged Current Cross-sections on helium, carbon, iron, lead and scintillator"
- 24) "Structure Functions on Scintillator from 2-20GeV"

- Preparing now for continued data taking in the high-energy beam starting this summer
 - Increased statistics, but also expanded physics reach at higher energies

The MINERvA Detector Calibration and Performance

L. Aliaga^a, A. Bodek^c, R. Bradford^c, H. Budd^c, A. Butkevich¹, D.A.M. Caicedo^e,
C.M. Castromonte^e, M.E. Christy^f, J. Chvojka^c, H. da Motta^e, D.S. Damiani^a, M. Datta^f,
R. DeMaat^g, J. Devan^a, S.A. Dytman^h, G. A. Díaz^b, B. Eberly^h, D.A. Edmondson^a,
J. Felixⁱ, L. Fields^j, G. A. Fiorentini^e, A. M. Gagoⁿ, H. Gallagher^l, B. Gobbi^j, R. Gran^m.

Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

L. Fields,¹ J. Chvojka,² L. Aliaga,^{3, 4} O. Altinok,⁵ A. Bodek,² D. Boehlein,⁶ R. Bradford,² W.K. Brooks,⁷
H. Budd,² A. Butkevich,⁸ D.A.M. Caicedo,⁹ C.M. Castromonte,⁹ M.E. Christy,¹⁰ H. da Motta,⁹ D.S. Damiani,³
I. Danko,¹¹ M. Datta,¹⁰ M. Day,² R. DeMaat,^{6, *} J. Devan,³ G.A. Díaz,⁴ S.A. Dytman,¹¹ B. Eberly,¹¹
D.A. Edmondson,³ J. Felix,¹² T. Fitzpatrick,^{6, *} G.A. Fiorentini,⁹ A.M. Gago,⁴ H. Gallagher,⁵ B. Gobbi,^{1, *}
R. Gran,¹³ D.A. Harris,⁶ A. Higuera,¹² I.J. Howley,³ K. Hurtado,^{9, 14} M. Jenkins,¹⁵ T. Kafka,⁵ M.O. Kanter,³
C. Keppel,¹⁰ M. Kordosky,⁵ A.H. Krajeski,⁵ S.A. Kulagin,⁹ T. Le,¹⁷ A.G. Leister,⁵
S. Manly,² J.G. Marshall,⁴ C.D. O'Connor,⁵ L. Rakoto,¹ D.W. Schmitz,^{2, 3} P. A. Rodrigues,⁴ L. Aliaga,^{5, 6} O. Altinok,⁷ A. Bodek,⁴ D. Boehlein,³
R. Bradford,⁴ W.K. Brooks,⁸ H. Budd,⁴ A. Butkevich,⁹ D.A.M. Caicedo,¹ C.M. Castromonte,¹ M.E. Christy,¹⁰
J. Chvojka,⁴ H. da Motta,¹ D.S. Damiani,⁵ I. Danko,¹¹ M. Datta,¹⁰ M. Day,⁴ R. DeMaat,^{3, *} J. Devan,⁵
G.A. Díaz,⁶ S.A. Dytman,¹¹ B. Eberly,¹¹ D.A. Edmondson,⁵ J. Felix,¹² L. Fields,¹³ T. Fitzpatrick,^{3, *} A.M. Gago,⁶
H. Gallagher,⁷ B. Gobbi,^{13, *} R. Gran,¹⁴ D.A. Harris,³ A. Higuera,¹² I.J. Howley,⁵ K. Hurtado,^{1, 15} M. Jenkins,¹⁶
T. Kafka,⁷ M.O. Kanter,⁵ C. Keppel,¹⁰ M. Kordosky,⁵ A.H. Krajeski,⁵ S.A. Kulagin,⁹ T. Le,¹⁷ A.G. Leister,⁵
G. Maggi,^{8, †} E. Maher,¹⁸ S. Manly,⁴ W.A. Mann,⁷ C.M. Marshall,⁴ K.S. McFarland,^{4, 3} C.L. McGivern,¹¹
A.M. McGowan,⁴ A. Mislivec,⁴ J.G. Morffin,³ J. Mousseau,¹⁹ D. Naples,¹¹ J.K. Nelson,⁵ G. Niculescu,²⁰
I. Niculescu,²⁰ N. Ochoa,⁶ C.D. O'Connor,⁵ J. Osta,³ J.L. Palomino,¹ V. Paolone,¹¹ J. Park,⁴ C.E. Patrick,¹³
G.N. Perdue,⁴ C. Peña,⁸ L. Rakotondravohitra,³ R. D. Ransome,¹⁷ H. Ray,¹⁹ L. Ren,¹¹ K.E. Sassin,⁵
H. Schellman,¹³ R.M. Schneider,⁵ E.C. Schulte,^{17, ‡} P. Sedita,⁴ C. Simon,²¹ F.D. Snider,³ M.C. Snyder,⁵
J.T. Sobczyk,^{22, 3} C.J. Solano Salinas,¹⁵ N. Tagg,²³ W. Tan,¹⁰ B.G. Tice,¹⁷ G. Tzanakos,^{24, *} J.P. Velásquez,⁶
J. Walding,^{5, §} T. Walton,¹⁰ J. Wolcott,⁴ B.A. Wolthuis,⁵ G. Zavala,¹² D. Zhang,⁵ and B.P. Ziemer²¹

Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

(The MINERvA Collaboration)

Thank you !

Backups

Systematics - Antineutrino

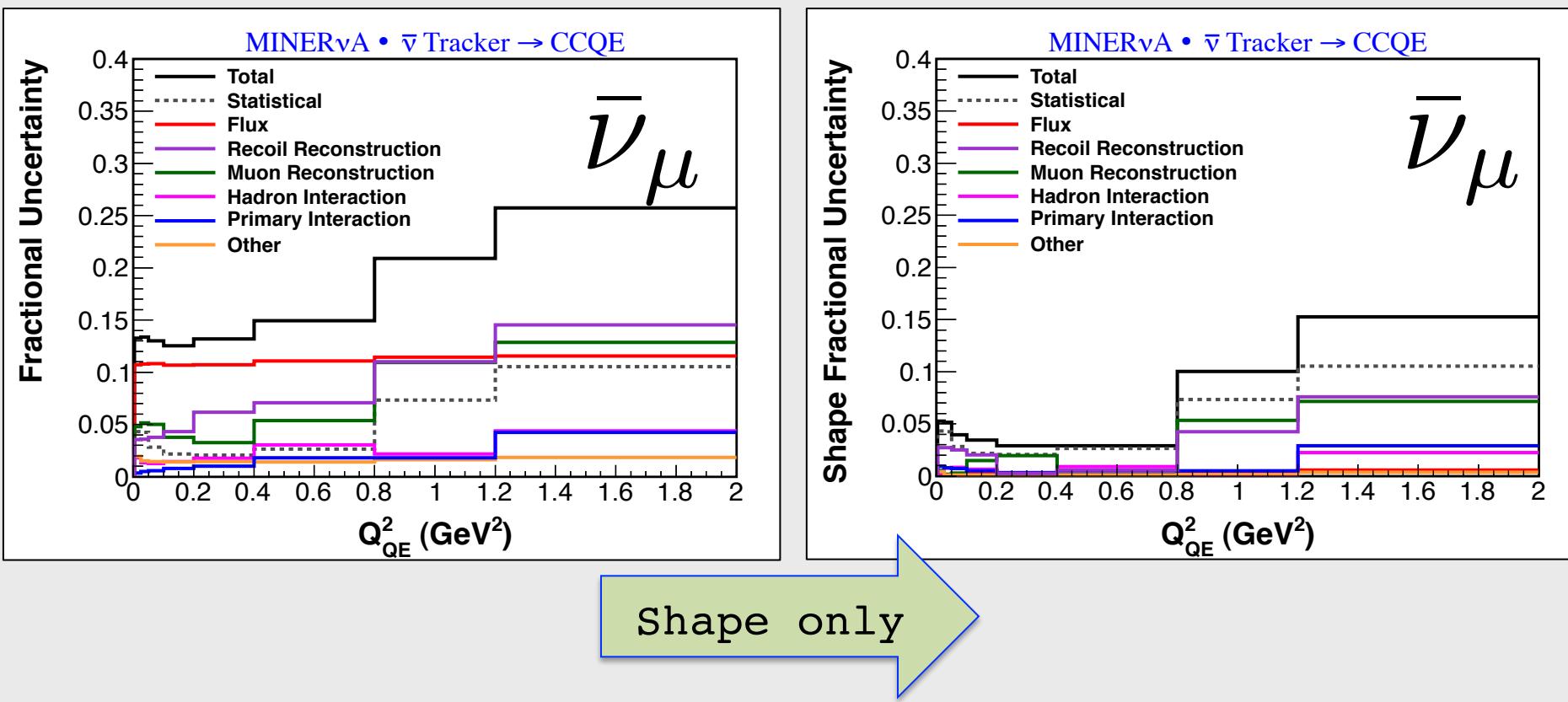
$\bar{\nu}_\mu$

Q_{QE}^2 (GeV 2)	I	II	III	IV	V	VI	Total
0.0 – 0.025	0.05	0.04	0.00	0.02	0.11	0.02	0.13
0.025 – 0.05	0.05	0.04	0.01	0.01	0.11	0.02	0.13
0.05 – 0.1	0.05	0.04	0.01	0.01	0.11	0.01	0.13
0.1 – 0.2	0.04	0.04	0.01	0.01	0.11	0.01	0.12
0.2 – 0.4	0.03	0.06	0.01	0.02	0.11	0.01	0.13
0.4 – 0.8	0.05	0.07	0.02	0.03	0.11	0.01	0.15
0.8 – 1.2	0.11	0.11	0.02	0.02	0.11	0.02	0.20
1.2 – 2.0	0.13	0.15	0.04	0.04	0.12	0.02	0.23

TABLE I: Fractional systematic uncertainties on $d\sigma/dQ_{QE}^2$ associated with muon reconstruction (I), recoil reconstruction (II), neutrino interaction models (III), final state interactions (IV), flux (V) and other sources (VI). The final column shows the total fractional systematic uncertainty due to all sources.

Systematics - Antineutrino

- Restricting to the *shape* of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



Systematics - Neutrino

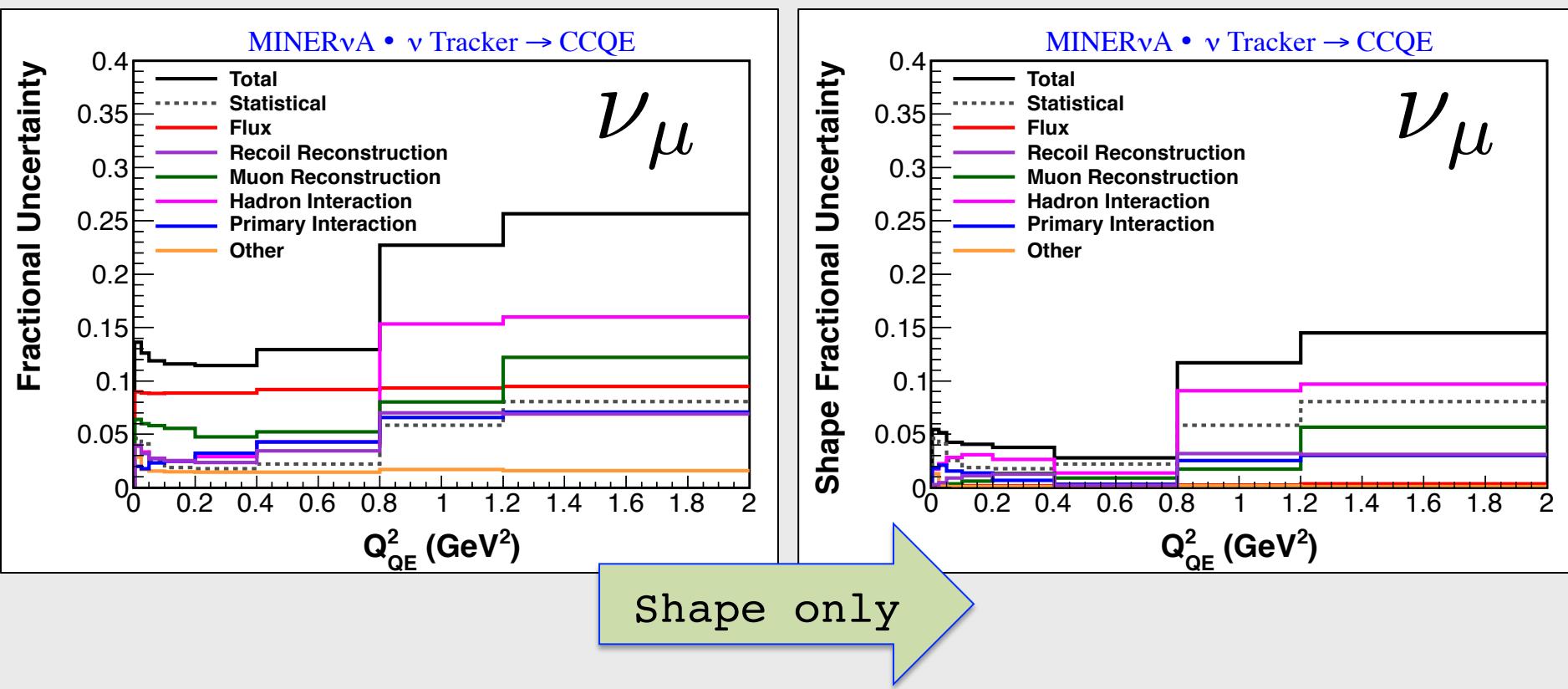
ν_μ

Q_{QE}^2 (GeV 2)	I	II	III	IV	V	VI	Total
0.0 – 0.025	0.06	0.04	0.02	0.04	0.09	0.03	0.13
0.025 – 0.05	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.05 – 0.1	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.1 – 0.2	0.06	0.03	0.03	0.02	0.09	0.02	0.11
0.2 – 0.4	0.05	0.02	0.03	0.03	0.09	0.01	0.11
0.4 – 0.8	0.05	0.03	0.04	0.04	0.09	0.01	0.13
0.8 – 1.2	0.08	0.07	0.07	0.15	0.09	0.02	0.22
1.2 – 2.0	0.12	0.07	0.07	0.16	0.09	0.02	0.24

TABLE I: Fractional systematic uncertainties on $d\sigma/dQ_{QE}^2$ associated with (I) muon reconstruction, (II) recoil reconstruction, (III) neutrino interaction models, (IV) final state interactions, (V) flux and (VI) other sources. The rightmost column shows the total fractional systematic uncertainty due to all sources.

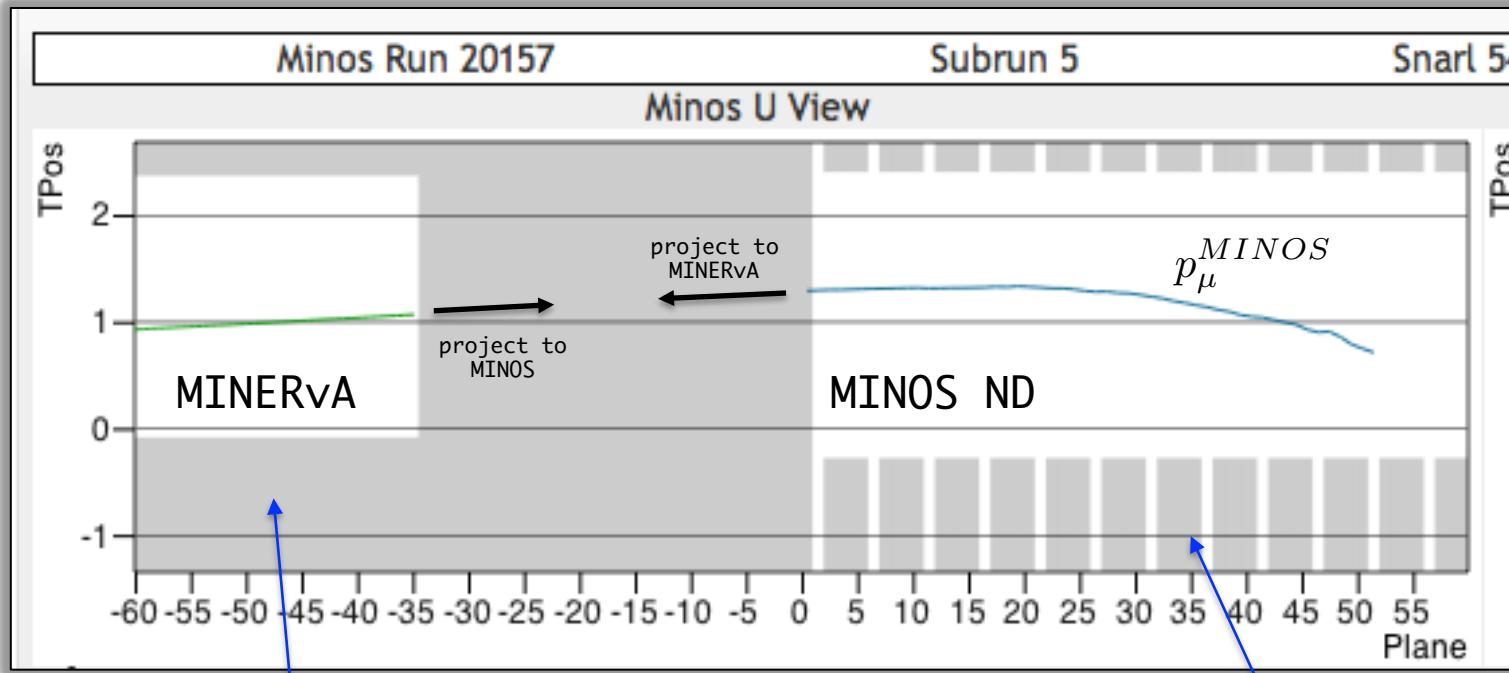
Systematics - Neutrino

- Restricting to the *shape* of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



Muon Tracking Efficiency

- Important to verify simulation of efficiencies against data wherever possible



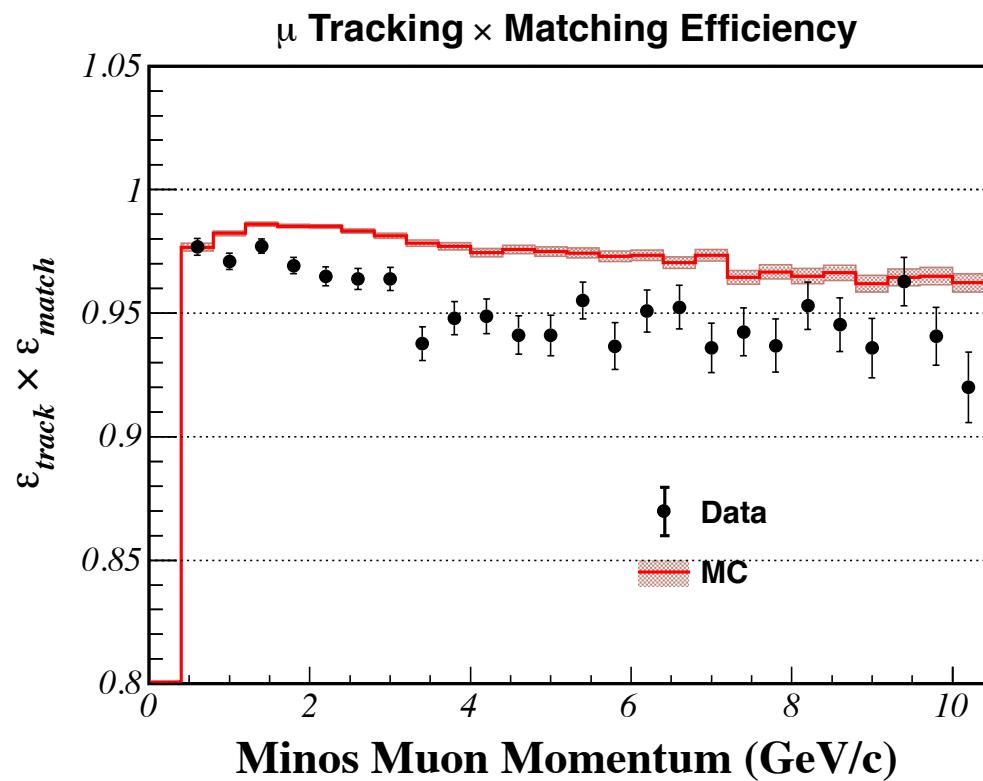
Affected by:

1. pile-up at high intensity
2. dead-time
3. large showers

Affected by:

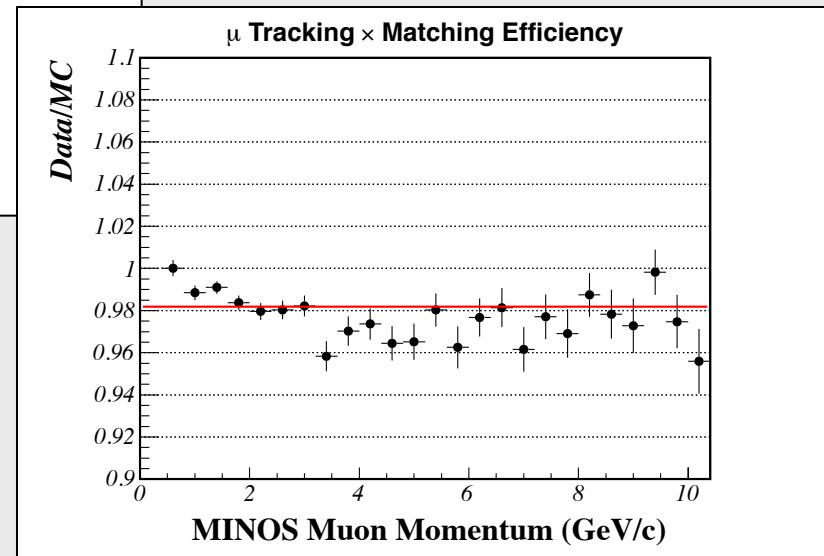
1. pile-up at high intensity, worse for shorter tracks (low energy)

Muon Tracking Efficiency



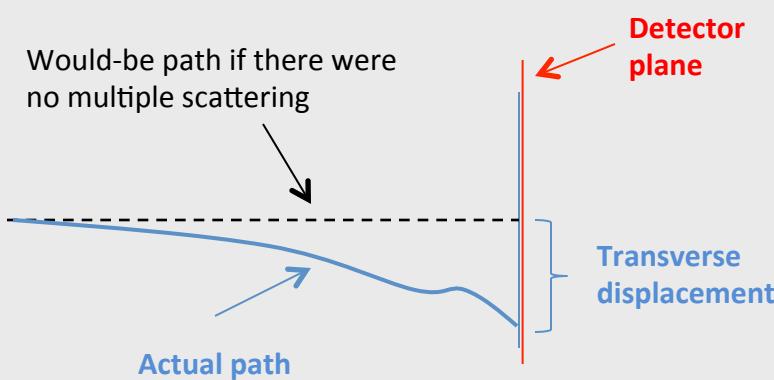
MINERvA muon tracking efficiency

Momentum provided by MINOS ND



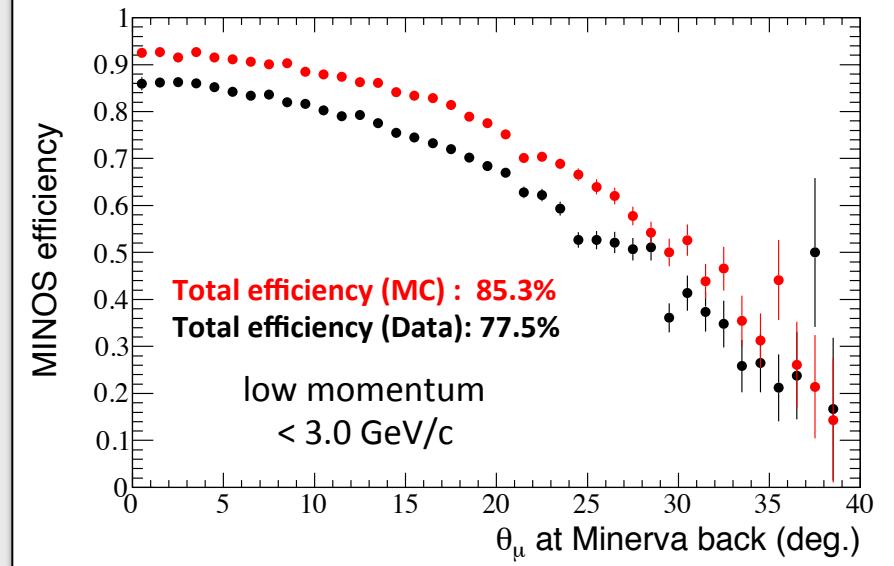
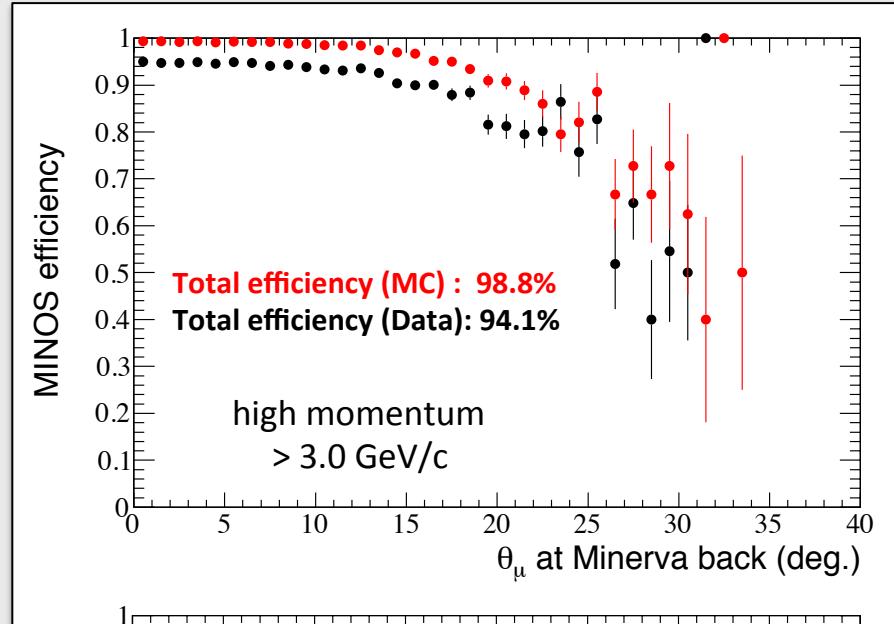
Muon Tracking Efficiency

MINOS muon tracking efficiency



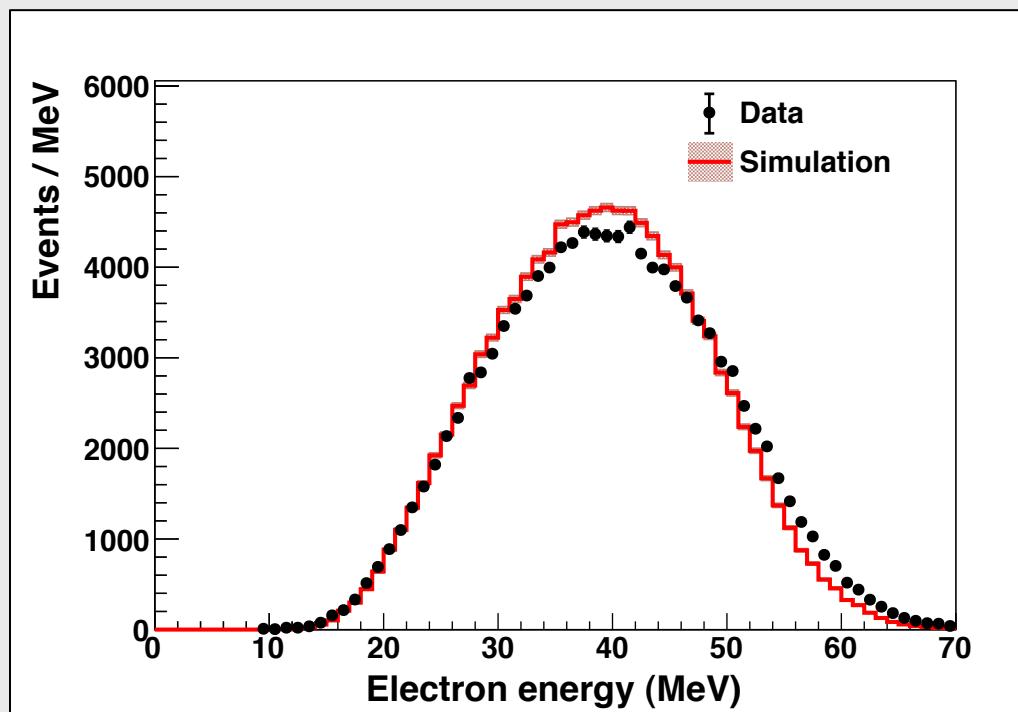
use scattering in MINERvA
ECAL+HCAL to split into **high**
and **low** momentum samples

Total Corrections	neutrinos	antineutrinos
$p_\mu < 3.0 \text{ GeV}/c$	$(-10.1 \pm 4.7) \%$	$(-7.8 \pm 3.4) \%$
$p_\mu > 3.0 \text{ GeV}/c$	$(-6.7 \pm 2.6) \%$	$(-4.5 \pm 1.9) \%$



Electromagnetic Energy Scale

20 – 60 MeV electrons



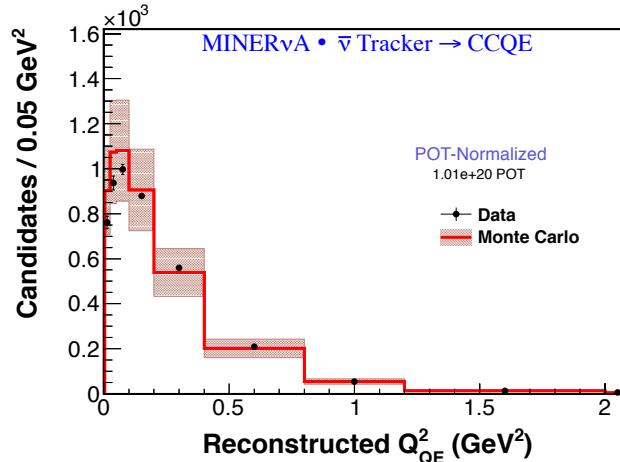
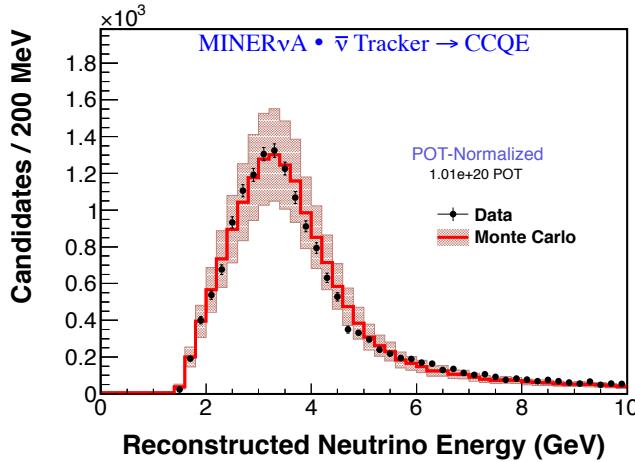
electromagnetic response
uncertainty $\approx 3\%$

QE Event Candidates

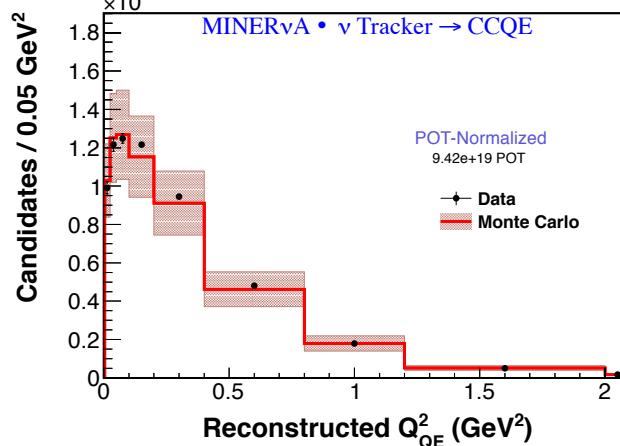
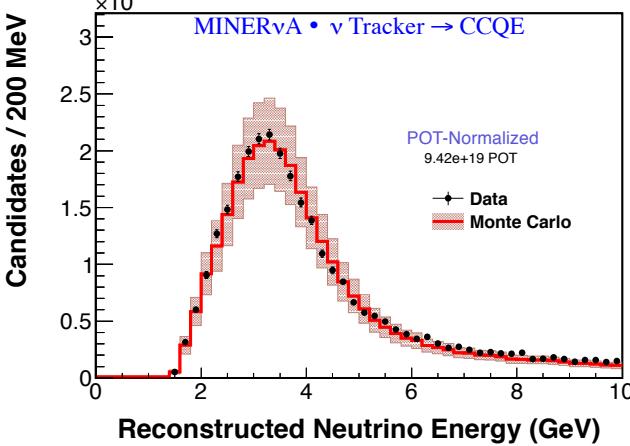
$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - [(M_n - E_B)^2 + m_\mu^2 - M_p^2]}{2[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$

$\bar{\nu}_\mu$



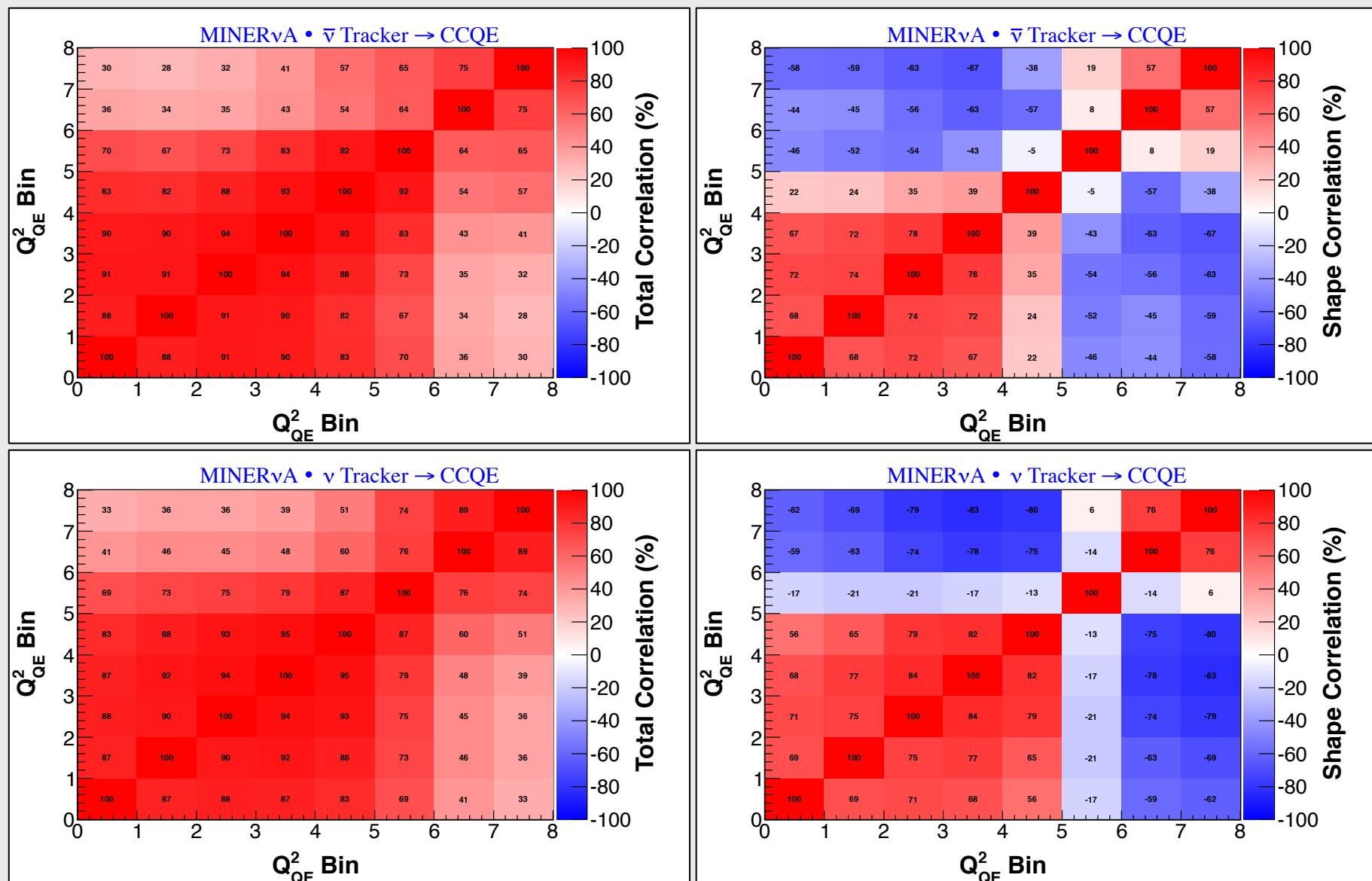
16,467 events
54% eff.
77% purity



ν_μ

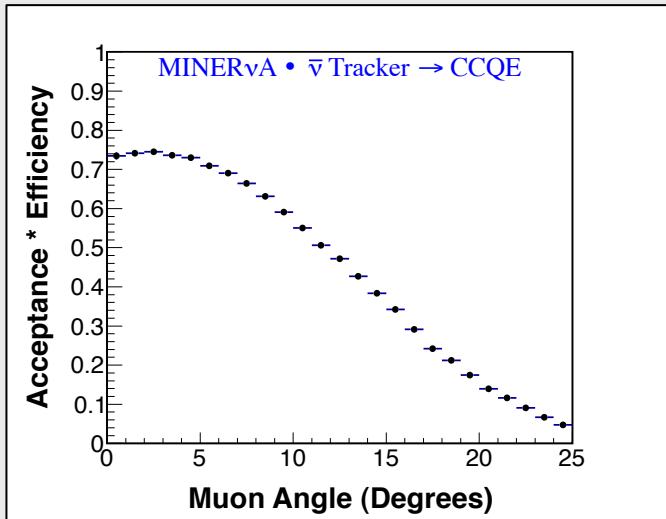
29,620 events
47% eff.
49% purity

Correlation Matrices

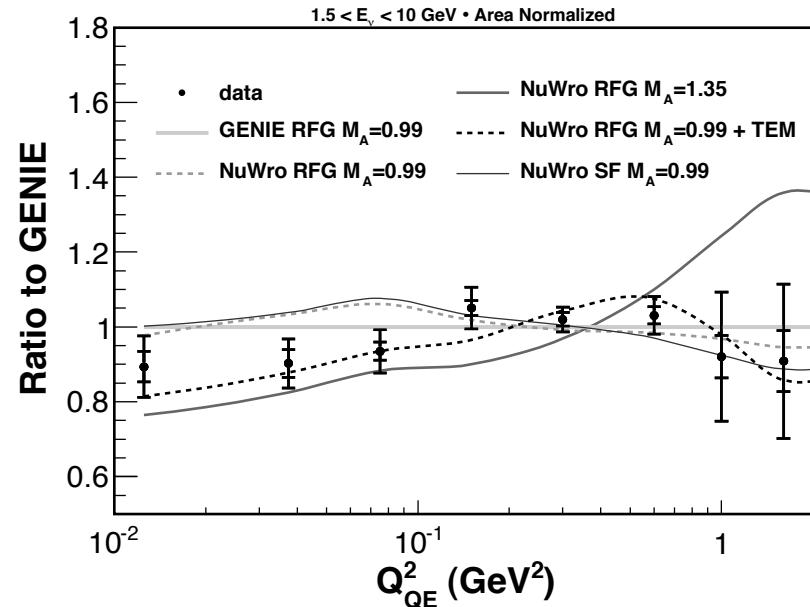
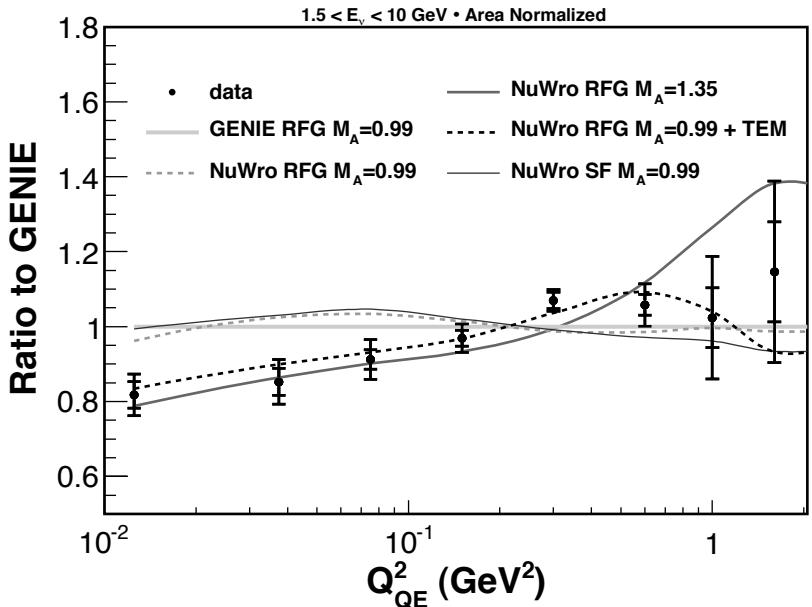
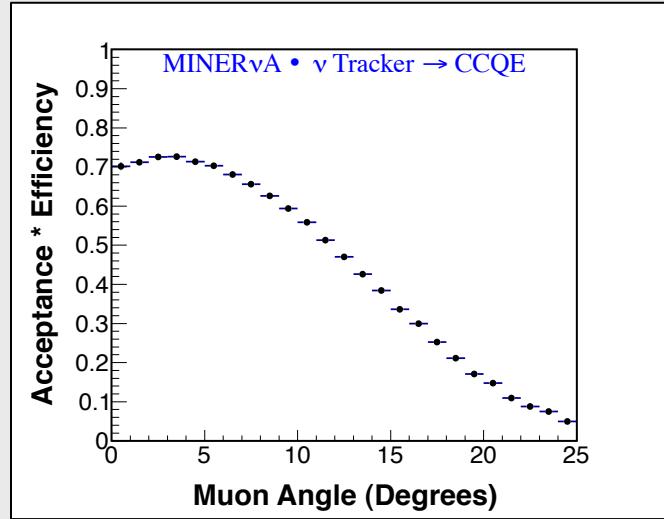


20 Degree Acceptance

$\bar{\nu}_\mu$

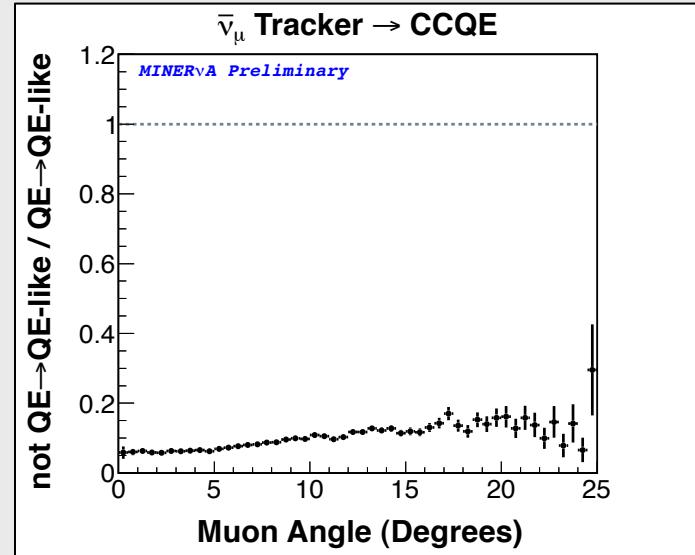
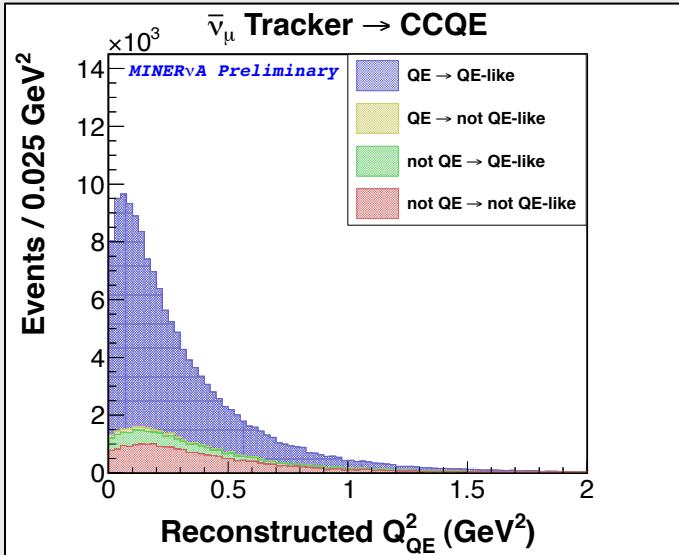


ν_μ

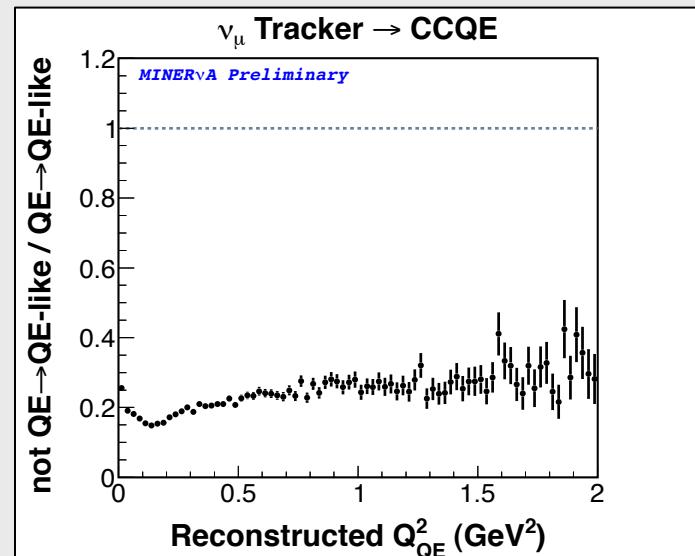
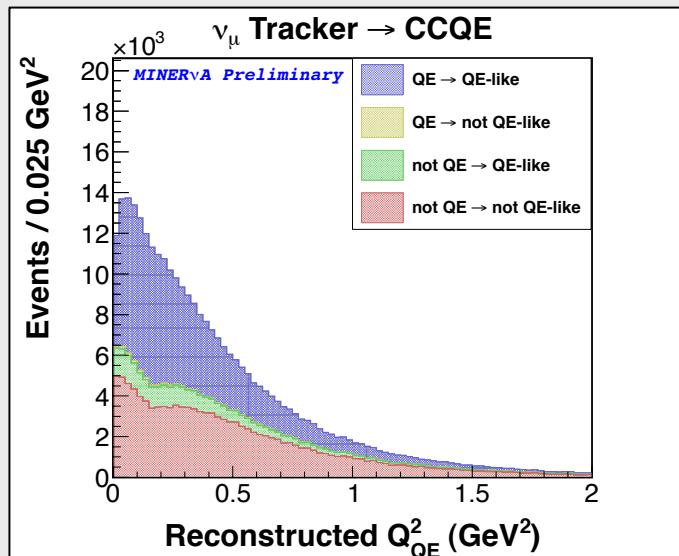


QE vs. QE-like

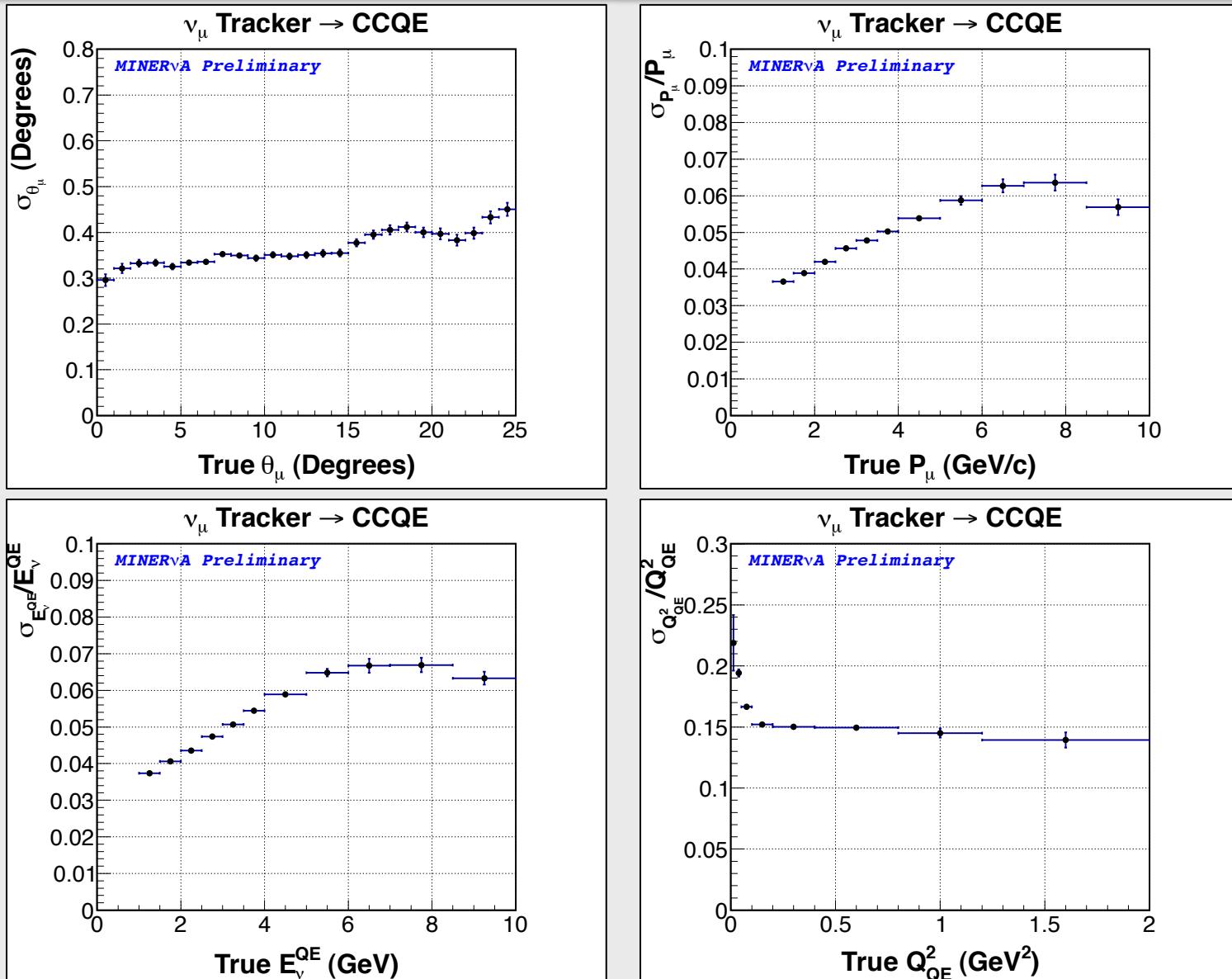
$\bar{\nu}_\mu$



ν_μ



Resolutions

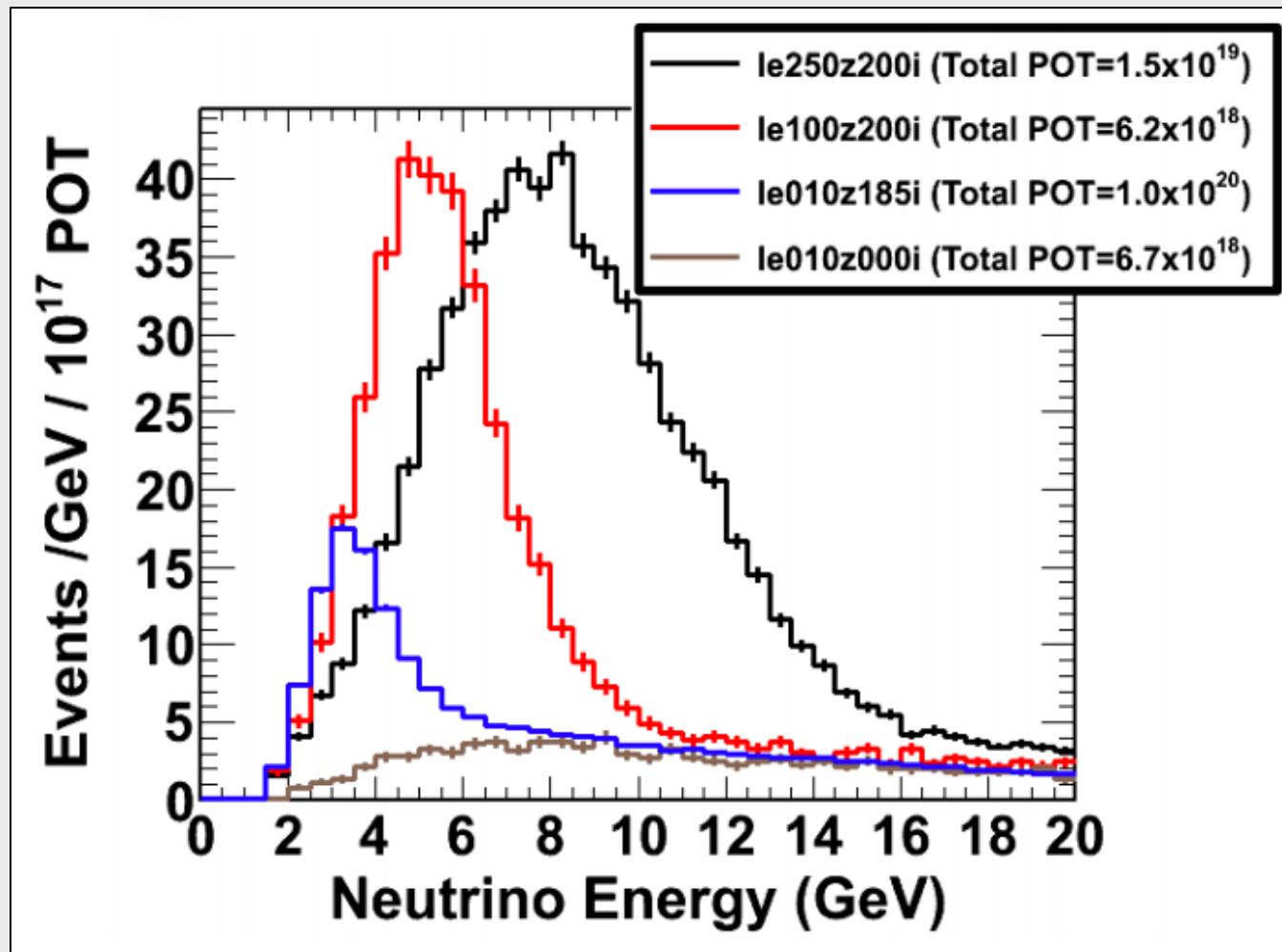


GENIE Uncertainties

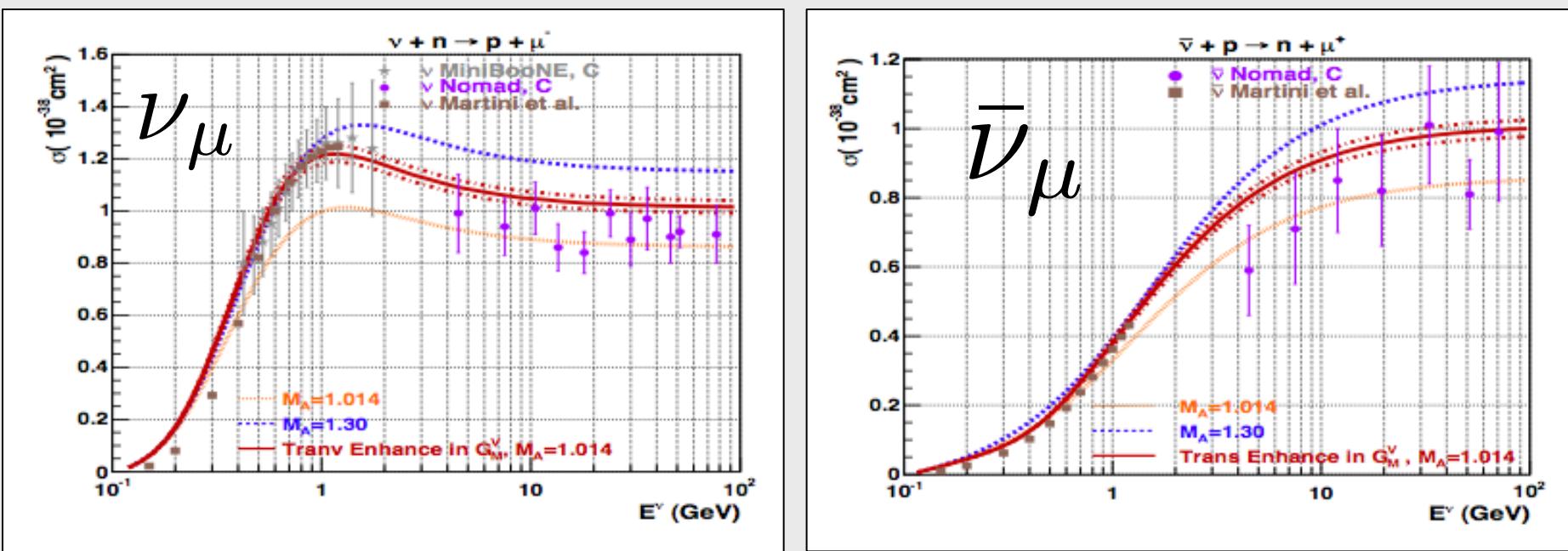
Uncertainty	GENIE Knob name	1σ
M_A (Elastic Scattering)	MaNCEL	$\pm 25\%$
Eta (Elastic scattering)	EtaNCEL	$\pm 30\%$
M_A (CCQE Scattering)	MaCCQE	$+25\%$ -15%
CCQE Normalization	NormCCQE	$+20\%$ -15%
M_A (CCQE Scattering, shape only)	MaCCQEshape	$\pm 10\%$
CCQE Vector Form factor model	VecFFCCQEshape	
CC Resonance Normalization	NormCCRES	$\pm 20\%$
M_A (Resonance Production)	MaRES	$\pm 20\%$
M_V (Resonance Production)	MvRES	$\pm 10\%$
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	Rvp1pi	$\pm 50\%$
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	Rvn1pi	$\pm 50\%$
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	Rvp2pi	$\pm 50\%$
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	Rvn2pi	$\pm 50\%$
DIS CC Normalization	NormDISCC	??
Modify Pauli blocking (CCQE) at low Q^2	CCQEPAULISUPVIAKF	$\pm 30\%$

Uncertainty	GENIE Knob name	1σ
Pion mean free path	MFP_pi	$\pm 20\%$
Nucleon mean free path	MFP_N	$\pm 20\%$
Pion fates – absorption	FrAbs_pi	$\pm 30\%$
Pion fates – charge exchange	FrCEx_pi	$\pm 50\%$
Pion fates – Elastic	FrElas_pi	$\pm 10\%$
Pion fates – Inelastic	FrInel_pi	$\pm 40\%$
Pion fates – pion production	FrPiProd_pi	$\pm 20\%$
Nucleon fates – charge exchange	FrCEx_N	$\pm 50\%$
Nucleon fates – Elastic	FrElas_N	$\pm 30\%$
Nucleon fates – Inelastic	FrInel_N	$\pm 40\%$
Nucleon fates – absorption	FrAbs_N	$\pm 20\%$
Nucleon fates – pion production	FrPiProd_N	$\pm 20\%$
AGKY hadronization model – x_F distribution	AGKYxF1pi	$\pm 20\%$
Delta decay angular distribution	Theta_Delta2Npi	On/off
Resonance decay branching ratio to photon	RDecBR1gamma	$\pm 50\%$

Special Run Data

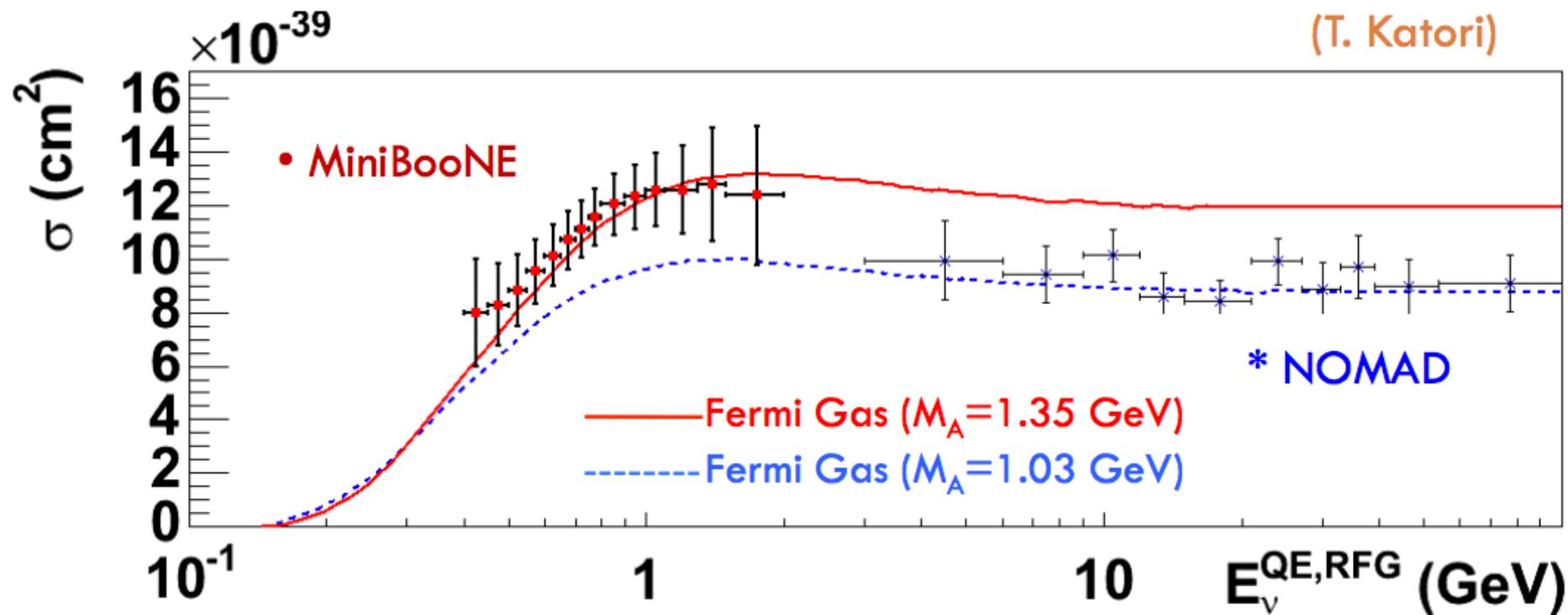


Transverse Enhancement Model

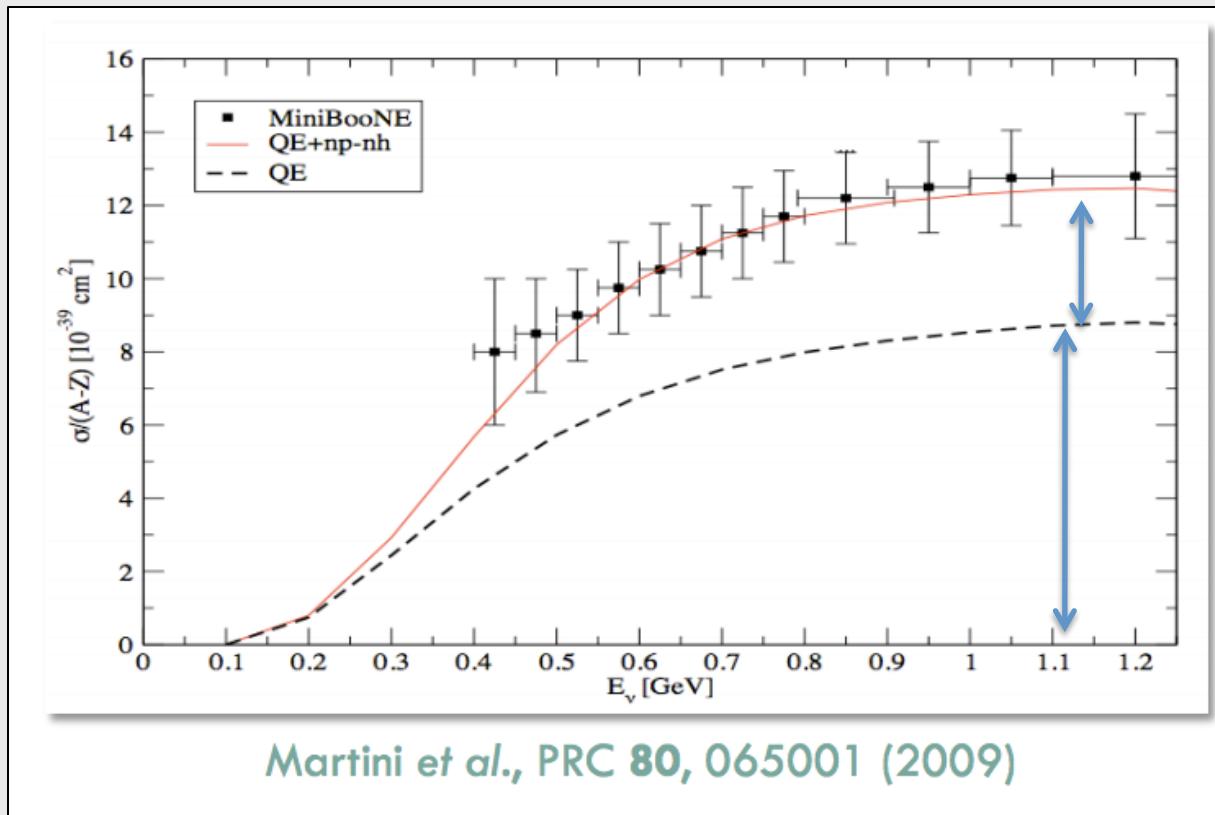


Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

MiniBooNE vs. NOMAD



2p2h in MiniBooNE



J.A. Formaggio and G.P.
Zeller, Rev. Mod. Phys.
84, 1307-1341, 2012

$\nu_\mu / \bar{\nu}_\mu$ CC total

ν_μ CCQE

$\bar{\nu}_\mu$ CCQE

